# NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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**REPORT No. 490**

# THE WEATHERING OF ALUMINUM ALLOY SHEET MATERIALS USED IN AIRCRAFT

By WILLARD MUTCHLER

1934

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# AERONAUTIC SYMBOLS

## 1. FUNDAMENTAL AND DERIVED UNITS

| | Symbol | Metric | | English | |
|---|---|---|---|---|---|
| | | Unit | Abbreviation | Unit | Abbreviation |
| Length | $l$ | meter | m | foot (or mile) | ft. (or mi.) |
| Time | $t$ | second | s | second (or hour) | sec. (or hr.) |
| Force | $F$ | weight of 1 kilogram | kg | weight of 1 pound | lb. |
| Power | $P$ | horsepower (metric) | | horsepower | hp. |
| Speed | $V$ | kilometers per hour | k.p.h. | miles per hour | m.p.h. |
| | | meters per second | m.p.s. | feet per second | f.p.s. |

## 2. GENERAL SYMBOLS

$W$, Weight $= mg$

$g$, Standard acceleration of gravity $= 9.80665$ m/s$^2$ or 32.1740 ft./sec.$^2$

$m$, Mass $= \frac{W}{g}$

$I$, Moment of inertia $= mk^2$. (Indicate axis of radius of gyration $k$ by proper subscript.)

$\mu$, Coefficient of viscosity

$\nu$, Kinematic viscosity

$\rho$, Density (mass per unit volume)

Standard density of dry air, 0.12497 kg-m$^{-4}$-s$^2$ at 15° C. and 760 mm; or 0.002378 lb.-ft.$^{-4}$ sec.$^2$

Specific weight of "standard" air, 1.2255 kg/m$^3$ or 0.07651 lb./cu.ft.

## 3. AERODYNAMIC SYMBOLS

$S$, Area

$S_w$, Area of wing

$G$, Gap

$b$, Span

$c$, Chord

$\frac{b^2}{S}$, Aspect ratio

$V$, True air speed

$q$, Dynamic pressure $= \frac{1}{2}\rho V^2$

$L$, Lift, absolute coefficient $C_L = \frac{L}{qS}$

$D$, Drag, absolute coefficient $C_D = \frac{D}{qS}$

$D_o$, Profile drag, absolute coefficient $C_{D_o} = \frac{D_o}{qS}$

$D_i$, Induced drag, absolute coefficient $C_{D_i} = \frac{D_i}{qS}$

$D_p$, Parasite drag, absolute coefficient $C_{D_p} = \frac{D_p}{qS}$

$C$, Cross-wind force, absolute coefficient $C_C = \frac{C}{qS}$

$R$, Resultant force

$i_w$, Angle of setting of wings (relative to thrust line)

$i_t$, Angle of stabilizer setting (relative to thrust line)

$Q$, Resultant moment

$\Omega$, Resultant angular velocity

$\rho\frac{Vl}{\mu}$, Reynolds Number, where $l$ is a linear dimension (e.g., for a model airfoil 3 in. chord, 100 m.p.h. normal pressure at 15° C., the corresponding number is 234,000; or for a model of 10 cm chord, 40 m.p.s. the corresponding number is 274,000)

$C_p$, Center-of-pressure coefficient (ratio of distance of *c.p.* from leading edge to chord length)

$\alpha$, Angle of attack

$\epsilon$, Angle of downwash

$\alpha_o$, Angle of attack, infinite aspect ratio

$\alpha_i$, Angle of attack, induced

$\alpha_a$, Angle of attack, absolute (measured from zero-lift position)

$\gamma$, Flight-path angle

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By WILLARD MUTCHLER
National Bureau of Standards

63519—34——1

# NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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# REPORT No. 490

## THE WEATHERING OF ALUMINUM ALLOY SHEET MATERIALS USED IN AIRCRAFT

By Willard Mutchler


### SUMMARY

*The investigation of the corrosion of aluminum alloy sheet materials used in aircraft was begun at the Bureau of Standards in 1925, at the request of its sponsoring governmental agencies, viz, the Bureau of Aeronautics, Navy Department, the Army Air Corps, and the National Advisory Committee for Aeronautics. It has for its purpose the study of the causes of corrosion embrittlement in duralumin-type alloys and the development of methods for its elimination.*

*The present report contains results, obtained in an extensive series of weather-exposure tests, which reveal the extent to which the resistance of the materials to corrosion was affected by variable factors in their heat treatment and by the application of various surface protective coatings. The results indicate that the sheet materials are to be regarded as thoroughly reliable, from the standpoint of their permanence in service, provided proper precautions are taken to render them corrosion-resistant.*


### INTRODUCTION

The impetus toward improvements in aircraft construction originating during the World War has persisted to the present day. During the war betterments in design were of primary importance. Materials of construction were given secondary consideration, since airplanes were frequently destroyed in service or rendered obsolete by changes in design before any serious impairment in the properties of their materials had occurred. At the conclusion of the war wood was most widely used, although there was evident a definite trend toward all-metal construction.

Heat-treatable aluminum alloys, because of their desirable quality of high strength combined with low weight, rapidly came to be regarded as outstanding among the materials upon which future progress in all-metal aircraft construction depended. Duralumin sheet was accordingly used in lighter-than-air craft for practically the entire framework; and in airplanes for floats, fuselage, and wing coverings.

Instances of failure caused by corrosive attack, however, occasioned a period of reaction and a contention that this material was unsuitable for use in aircraft. The difficulties were experienced principally with sheet material and rivets, which became seriously embrittled. On occasions certain sheets would be rendered useless after a few months' service, while adjacent sheets exhibited no loss in physical properties. The behavior of the material seemed inexplicably erratic.

It was during this period of uncertainty that the investigation of corrosion embrittlement in sheet aluminum alloys was undertaken at the Bureau of Standards. The purposes of the investigation were twofold: First, to establish the causes of the deterioration by embrittlement of high-strength aluminum alloys in sheet form and more particularly the type of corrosive attack designated as intercrystalline; and second, to study methods of retarding or eliminating this deterioration.

In the earlier stages of the work short-time laboratory corrosion tests constituted the principal approach to these problems and yielded information of considerable value. But such tests, however carefully performed, cannot be expected to reproduce accurately specific conditions of service. The results obtained could at best be regarded as only qualitative indications of the possible behavior in service. The need for confirmatory service data became more apparent as the laboratory corrosion tests progressed. The only practical way to obtain systematic data of this kind consisted in the exposure of materials to the weather. This course was followed and this report consists largely of a discussion of the results obtained in the weather-exposure tests, together with some correlation with the results obtained in the laboratory. The results of the latter have already been reported upon in some detail (references 1 to 7).

It may be stated at the outset that the results obtained in the present investigation warrant confidence in the dependability of properly prepared duralumin as a material for aircraft construction, and afford a foundation for the understanding of its behavior under corrosive conditions.

### MATERIALS

Most of the tests were carried out upon 14-gage sheet duralumin, 0.064 inch thick, and the results obtained are strictly applicable only to materials of this thickness. The term "duralumin" is frequently loosely

used to refer to any of the strong aluminum alloys. Its use here is restricted to wrought aluminum-base alloys containing approximately 4 percent copper, 0.5 percent magnesium, 0.5 percent manganese, together with small amounts of iron and silicon, that result from impurities in the aluminum. The chemical compositions of the principal materials used are given in table I. The alloys designated as 17S and B were furnished by two American manufacturers and are representative of commercial duralumin. Most of the remaining alloys were included principally to determine the effects of changes in composition upon the corrosion resistance.

Alloy I-1 was a specially prepared duralumin in which the iron-silicon ratio was controlled so as to be about 1 : 1. The combined content of these two elements was also appreciably lower than is usual in commercial duralumin. Alloy I-2 was prepared under commercial conditions from aluminum of very much higher purity than is ordinarily used for this purpose,

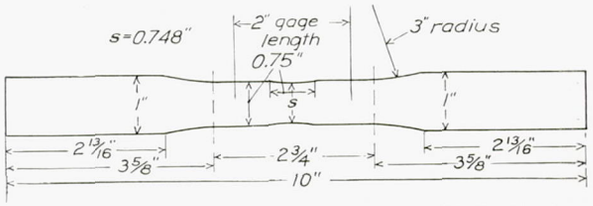



FIGURE 1.—Dimensions of the tensile specimens of the 0.064-inch-thick aluminum alloy sheet materials.

with the result that the iron and silicon contents were very low.

Alloy 58B differed from ordinary duralumin in having a lower copper content, and alloy 63A in having a higher iron content. Although prepared specifically for this investigation, both alloys were made in accordance with commercial manufacturing processes.

Alloys A17S and B17S are marketed commercially and may be regarded as modifications of duralumin. Like duralumin, they age-harden spontaneously at room temperatures, but are said to be more suitable for cold forming. Both alloys nominally contain approximately 0.3 percent magnesium and very little manganese. The A17S alloy has an even lower copper content (about 2.5 percent) than does the special alloy 58B. The strengths of neither of these alloys after age-hardening is as high as that of ordinary duralumin.

Alloy 51S, another commercial product, intended primarily for forgings, is essentially an aluminum-base alloy containing 1 percent silicon and 0.6 percent magnesium. A striking difference between 51S and duralumin is the almost complete absence of copper in the former. Although it age-hardens substantially at room temperature, reheating to about 150° C. is necessary for the development of maximum physical properties.

The alloy commercially designated as 25S nominally contains 4.5 percent copper, 0.8 percent silicon, and 0.8 percent manganese. Unlike duralumin, it contains no magnesium. Superior hot-working qualities are claimed for it. It has found extensive use in forged parts in which high stresses are encountered in service, such as aircraft propellers and connecting rods for internal combustion engines. The alloy does not age-harden appreciably at room temperatures, reheating to about 145° C. being required to produce maximum properties.

The tensile properties of the materials discussed above, in various conditions of heat treatment and prior to exposure to corrosive conditions, are contained in table II and summarized in figure 6.

## PREPARATION OF SPECIMENS

The initial step in the preparation of specimens consisted in machining them from strip material as received from the manufacturers. The tensile bars used in nearly all the tests had an over-all length of 10 inches and a reduced section ¾ inch wide which tapered to a width of 1 inch at the grip ends. The detailed dimensions of the specimens are shown diagrammatically in figure 1.

The machined tensile bars were given a preliminary annealing treatment by heating for 2¼ hours at 450° C. and cooling with the furnace. An electric-resistance furnace was used and no attempt was made to control the atmosphere within the muffle of the furnace.

The annealed specimens were subjected to a "solution heat treatment", which usually consisted in heating in a fused nitrate bath at 500° to 510° C. for a period of 15 minutes. Variations from this procedure, made for specific purposes, will be noted later.

After the solution heat treatment the specimens were quenched. Various quenching mediums were used, ice water and boiling water being by far the most frequently employed. Particular care was exercised in effecting all quenching rapidly. The quenched specimens, unless otherwise specifically noted, were permitted to age-harden at room temperatures for a minimum period of 2 weeks prior to the corrosion tests or before the determination of their "initial" properties. For those specimens to be exposed to the weather the aging period was approximately 3 months.

All specimens, prior to the application of additional coatings or before corrosion tests, were cleaned free from grease by washing twice with clean benzine and once with alcohol. All specimens to which the same treatments had been applied were designated as "sets" and were stamped with corresponding numbers. Protective surface coatings were applied to a number of sets of specimens. A limited number of sets were mechanically worked in various ways after aging.

## EXPERIMENTAL PROCEDURE

### GENERAL

A departure from the more commonly used methods in corrosion testing was utilized extensively in the present investigation. The method had been advocated by Blough (reference 8), and was perhaps first used by Basch and Sayre (reference 9). It consisted in the carrying out of corrosion tests upon tensile specimens that were machined to size prior to corrosion. It should be borne in mind, in considering the results which follow, that the tensile properties obtained on such bars after corrosion, are usually slightly lower than if the machining had been done after corrosion, because corrosion occurred on the cut edges of the machined specimen.

For each set of specimens a number of tensile bars were prepared. A few of these were tested to determine the average tensile properties of the uncorroded material. The remainder were subjected to corrosive conditions in either laboratory or weather-exposure tests, or both. The corroded bars were removed at intervals and tested. A comparison of the tensile properties of the corroded bars, with those of uncorroded bars, served as a measure of the corrosion. Elongation values were obtained over a central 2-inch gage length. Microscopic examinations were made to determine the nature and predominating type of corrosive attack, and the actual depth of penetration of the attack was measured on all specimens exposed to the weather.

Much of the information presented herein is in graphical form. The points appearing on the individual curves serve only for purposes of identification and to reveal the period at which specimens were withdrawn for test. On the curves which show the maximum depth of penetration of corrosive attack, the depth is expressed in terms of percent of half the thickness of the sheet.

### LABORATORY TESTS

The laboratory corrosion tests were performed almost exclusively by the intermittent-immersion method. This method was selected because: (1) Preliminary tests by the salt-spray method (reference 7) and by the continuous-immersion method (reference 2) had indicated that, although the results obtained were similar, both required longer periods than the intermittent-immersion method to produce equivalent losses in tensile properties; and (2) the alternate wetting and drying of the surfaces in the intermittent-immersion method simulated conditions existing in aircraft service more closely than would continued wetting.

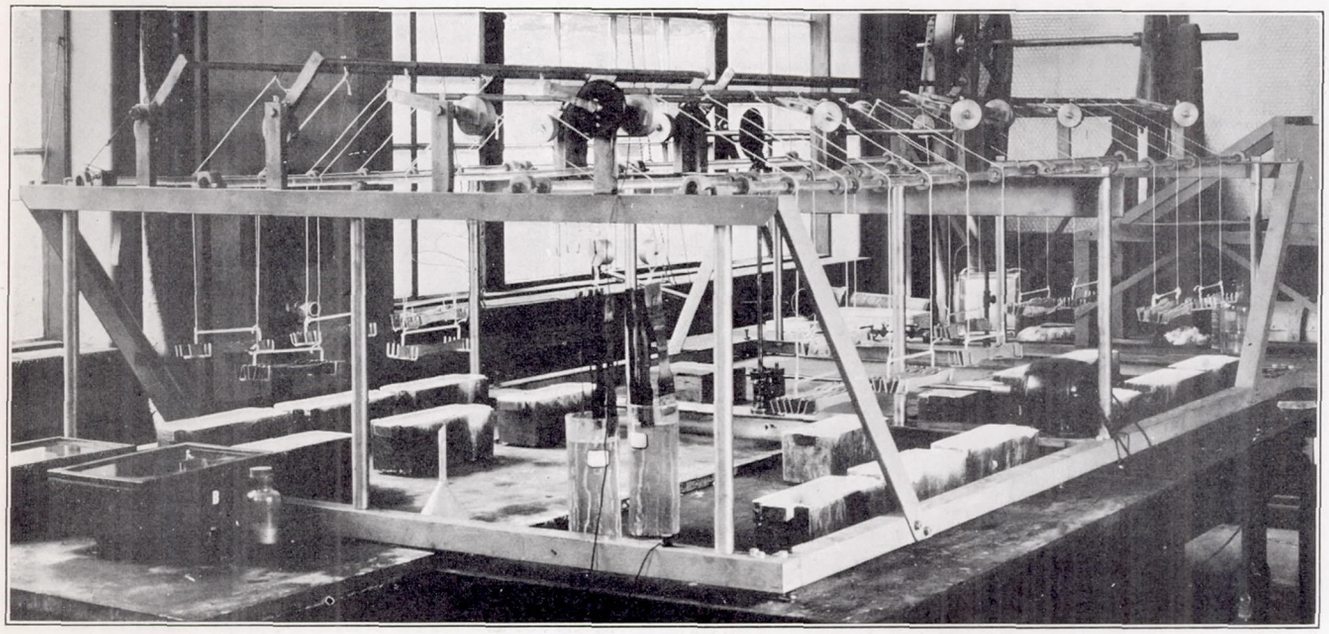


FIGURE 2.—Intermittent-immersion apparatus used in the laboratory corrosion tests.

The intermittent-immersion apparatus (fig. 2) has been described in detail (reference 2). The tensile specimens, supported horizontally on edge in a glass framework, were lowered periodically into the corrosive solution and then withdrawn into the air to dry. Each "wet and dry" cycle occupied 15 minutes, during about 14 minutes of which the specimens were suspended in the air.

Numerous intermittent-immersion tests were also conducted in specially developed apparatus which permitted the application of repeated flexural stress or static stress throughout the test periods. As these modified appliances have already been described (references 6 and 7), the results obtained will be touched upon only briefly in the present report.

A number of corroding mediums were employed in the intermittent-immersion tests but, owing to its rapid action, a solution consisting of 9 parts by volume of a normal sodium chloride solution and 1 of commercial hydrogen peroxide (3 percent) was most frequently utilized. The resultant solution was $0.9N$ in NaCl and 0.1 $M$ in $H_2O_2$.

### WEATHER-EXPOSURE TESTS

The racks for the weather-exposure tests were installed at three locations which represented typical climatic conditions, as follows:

(1) Bureau of Standards, Washington, D.C., representative of a temperate inland exposure, free from industrial contamination and from marine conditions.

(2) Naval Air Station, Hampton Roads, Va., representative of temperate seacoast conditions, with occasional contact with salt water.

(3) Fleet Air Base, Coco Solo, Canal Zone, representative of tropical seacoast conditions, with occasional contact with salt water.

The racks at the Bureau of Standards (fig. 3) were situated on a roof. They faced the south and were inclined at an angle of approximately 10° from the horizontal. The Coco Solo racks (fig. 4) faced the south and were inclined at an angle of about 45°. Their situation upon a breakwater on the Caribbean Sea assured occasional contact of the specimens with spray and less frequent thorough wettings during storms. The racks at Hampton Roads were located on a platform attached to the side of a pier, about 3 feet above highest tide, where the specimens were inclined at about 45° and subject to wettings as at Coco Solo.

Specimens exposed at Washington, D.C., and at Hampton Roads, Va., were withdrawn for test at intervals of 6 months over a 5-year period. Owing to the more severely corrosive conditions at Coco Solo, the specimens were withdrawn at shorter intervals. After 37 months the specimens which remained were lost during a severe storm.

FIGURE 3.—Weather-exposure racks and specimens on the roof of the northwest building at the Bureau of Standards, Washington, D.C.

At all three locations the exposure of the two surfaces of the specimens necessarily differed somewhat, owing to the fact that one surface invariably received the direct rays of the sun while the other did not. Since such a condition is frequently paralleled in service, it was not deemed desirable to change the positions of the specimens during the exposure periods.

### CONTROL SPECIMENS

Duplicate specimens of all sets included in the weather-exposure tests were kept in the laboratory in sealed glass containers and withdrawn at 6-month intervals over the 5-year period for comparison with

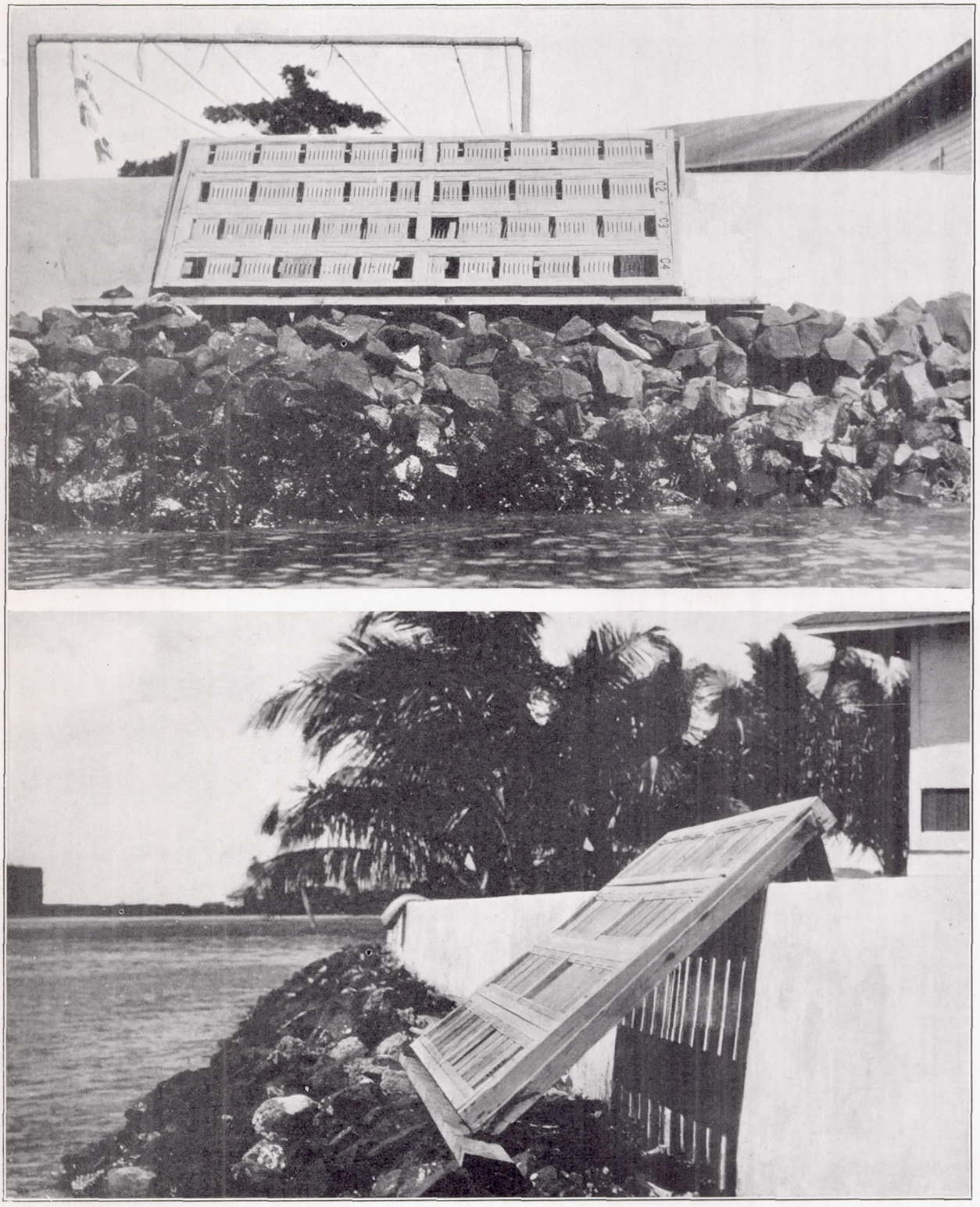


FIGURE 4.—Front and side views of the weather-exposure racks and specimens at Coco Solo, Canal Zone.

the exposed specimens. A dry atmosphere was maintained within the containers by the use of soda lime. The specimens were suspended in such a manner that they did not touch the dehydrating agent.

### STRENGTH-DUCTILITY RELATIONS IN CORRODED SPECIMENS

The exposure of upward of 2,500 specimens made it possible to determine with some accuracy the relative changes in physical properties resulting from corrosion, irrespective of both time and locality of exposure. The strength-ductility relations are summarized in figure 6. The curves reveal that the changes in tensile strength relative to elongation were practically the same for all the alloys tested. Corrosion resulted in lowering the elongation of the materials to approximately 40 percent of its initial value with accompanying losses in strength seldom exceeding 5,000 pounds per square inch. Additional losses in elongation were associated with rapid decreases in strength. It is noteworthy, also, that the data have indicated that marked losses in tensile strength do not occur in 14-gage sheet duralumin until corrosive attack has penetrated in excess of 20 percent of the thickness. Although no curves showing the relationships of the "yield points" of these alloys to the percentage of the initial elongation have been included, the data indicated that the effect of corrosion was even less than upon the tensile strength. Appreciable lowering of the "yield point" was not in evidence until the percent of the initial elongation fell considerably below 40.

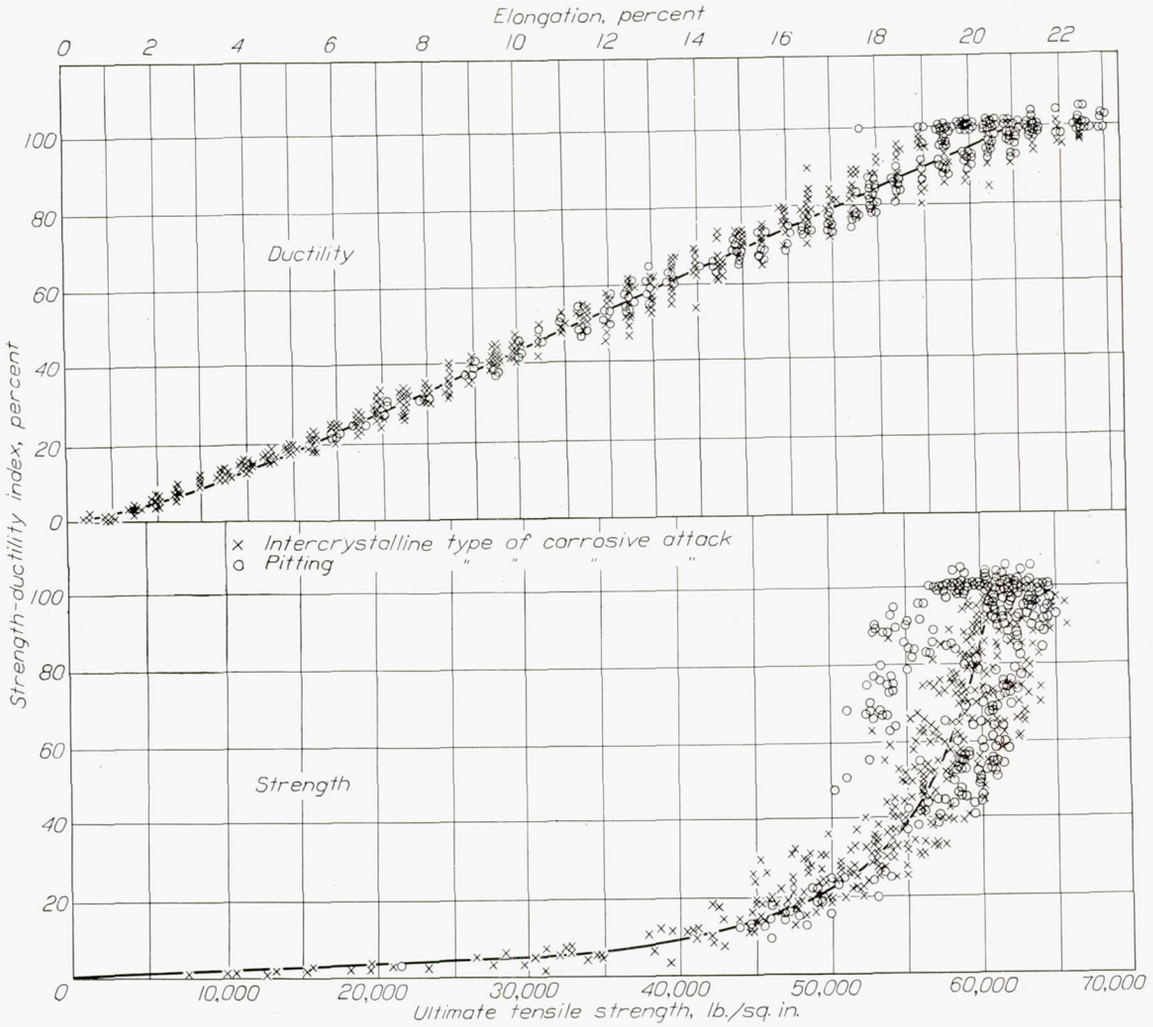



FIGURE 5.—Relations of strength-ductility index to physical properties of heat-treated duralumin exposed to the weather.

These results are indicative that severely corroded duralumin, with elongation values of from 8 to 10 percent, could be regarded as dependable for the support of heavy static loads. For service conditions conducive to sudden impact or repeated stresses the same material would be unsuitable because of the embrittlement caused by the lowered ductility.

Figure 5 is included to convey an idea as to the number and distribution of the plotted points on which, for example, curve *D* of figure 6 was based. The ordinate designation, the strength-ductility index, is practically proportional to the one used in figure 6. It may be defined as the ratio, on a percentage basis,

of the product of the tensile strength and elongation of the corroded specimen to the corresponding average product for the uncorroded specimens. The range of deviation of the physical properties, from the average value represented by the curves, is seen to be quite limited.

## FACTORS AFFECTING SUSCEPTIBILITY TO CORROSION

### RATE OF COOLING IN QUENCHING

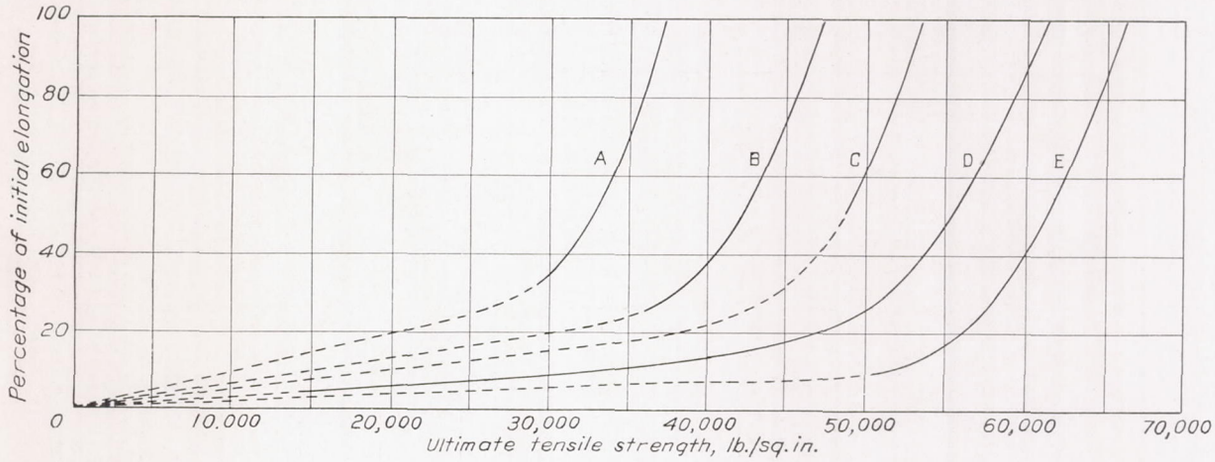
Knerr (reference 10) was probably the first to note that the susceptibility of duralumin to corrosion depends to some extent upon its condition of heat treatment and wrote that "the rate of cooling in heat treatment has a strong influence on its resistance to corrosion, as indicated by the salt-spray test." This was confirmed early in laboratory tests of the present investigation (reference 3), the results of which were in agreement with those obtained in the exposure tests. Sets of specimens in both types of corrosion tests were quenched in one of the following: (1) Ice water at 2° to 7° C.; (2) water at room temperature (approximately 25° C.); (3) boiling water; (4) oil at room temperature; and (5) oil cooled to approximately 0° C.

### LOSS IN PHYSICAL PROPERTIES

The results obtained on specimens exposed at Washington and Coco Solo are shown in figure 7, where the exceedingly important rôle played by the rate of cooling is apparent on a glance. The initial tensile properties of duralumin quenched in these various mediums were approximately identical after aging at room temperature. But quenching in cold water rendered sheet duralumin *very much more* resistant to corrosive attack, as evidenced by the rate of loss in physical properties, than did quenching in cold oil or in hot water, irrespective of the conditions of exposure.

For all practical purposes, duralumin quenched in water at 25° C. had a corrosion-resistance equivalent to that obtained by quenching in ice water, although the latter is to be recommended. Duralumin quenched in oil at 0° C. behaved practically the same as that quenched in oil at 25° C. After 5 years' exposure at Washington, duralumin quenched in cold water had retained more than 95 percent of its initial elongation. The comparable value of duralumin quenched in cold oil was only slighly in excess of 85 after somewhat more than a year's exposure, while that of material quenched in boiling water fell below 80 within 6 months and reached a value of 60 within 18 months. The exceptionally rapid rate of loss in ductility of duralumin quenched in cold oil or hot water, and exposed at Coco Solo, is especially to be noted. The ductility value fell below 70 in less than 3 months. These results may be considered typical of severe marine conditions in general.

It is noteworthy that the decrease in ductility of cold-water-quenched duralumin at Coco Solo was comparable with the rate at which the same material




| Alloy | Initial tensile properties | | Alloy | Initial tensile properties | |
|---|---|---|---|---|---|
| | Ultimate tensile strength | Elongation in 2 inches | | Ultimate tensile strength | Elongation in 2 inches |
| | *Lb./sq. in.* | *Percent* | | *Lb./sq. in.* | *Percent* |
| 51S | 35,500 | 27.0 | B17S | 52,000 | 23.0 |
| A17S | 38,500 | 22.0 | 25S | 55,000 | 21.5 |
| 17S (425° C.) | 47,000 | 19.0 | "Duralumin" | 62,000 | 20.5 |
| 63A | 52,000 | 18.0 | 17S (worked) | 66,000 | 12.0 |
| 58B | 52,000 | 20.5 | | | |

| *Curve* | *Average of alloys* |
|---|---|
| A | 51S–A17S. |
| B | 17S (heated at 425° C.). |
| C | 63A–B17S–58B–25S. |
| D | 17S–I–1–1–2–B ("Duralumin" alloys). |
| E | 17S (cold worked after aging). |

FIGURE 6.—Strength-ductility relations of 14-gage sheet aluminum alloys corroded in exposure tests after solution heat treatment at 500° to 520° C., quenching, and aging. Data lacking for the broken portions of the curves.

quenched in boiling water deteriorated at Washington. The need for additional protective coatings, under severe corrosive conditions, is therefore apparent.

From the foregoing, the necessity for a rapid rate of cooling from the solution heat treatment temperature is indicated. This condition is satisfied by the use of cold water, but not by the use of hot water or cold oil. Quenching in the latter two mediums is sometimes done in practice to reduce distortion due to internal stresses. For material of thick cross section this procedure may be satisfactory, but not for sheet material of the kind used in this investigation.

### TYPES OF CORROSIVE ATTACK

Two distinctive types of corrosive attack occur in duralumin. The first (fig. 8c), which has been termed the "pitting" type, is a purely superficial phenomenon analogous to the ordinary rusting of ferrous metals. The corrosive mediums result in the eating away of the surface metal with the formation of pits which bear no evident relationship to the structure of the metal. The second (fig. 8a), or intercrystalline, type of attack is particularly insidious, because it may begin at a relatively few and not easily discernible surface nuclei and, following the crystalline or grain boundaries, proceed deeply into the metal or entirely through sheet material. Intercrystalline attack was early shown (reference 11) to result in serious embrittlement in sheet duralumin and to be associated with certain incorrect methods of heat treatment (reference 3).

Occasionally, intercrystalline attack presents the appearance (fig. 8b) of having begun around the edges of a previously developed pit. It is usually to be inferred in this case that the attack was entirely of the intercrystalline type and that the pit resulted from the removal of the loosely adherent grains. More rarely, intercrystalline attack starts at the base of a relatively deep pit, probably indicating slow cooling of the interior of the metal as compared with the surface.

An intercrystalline attack also occurs in which the usual tendency to penetrate deeply seemingly ceases: the attack spreads laterally beneath the surface and results in localized bulging of the surface layer of the metal, as shown in figure 8e and f. The bulged layer falls off after a time, causing a characteristic saucer-shaped depression on the surface (fig. 9e and f). Meissner (reference 12) has described this as a distinctive type which he terms "pock-form" corrosion. Its occurrence is associated with those methods of heat treatment which involve reheating after the solution heat treatment.

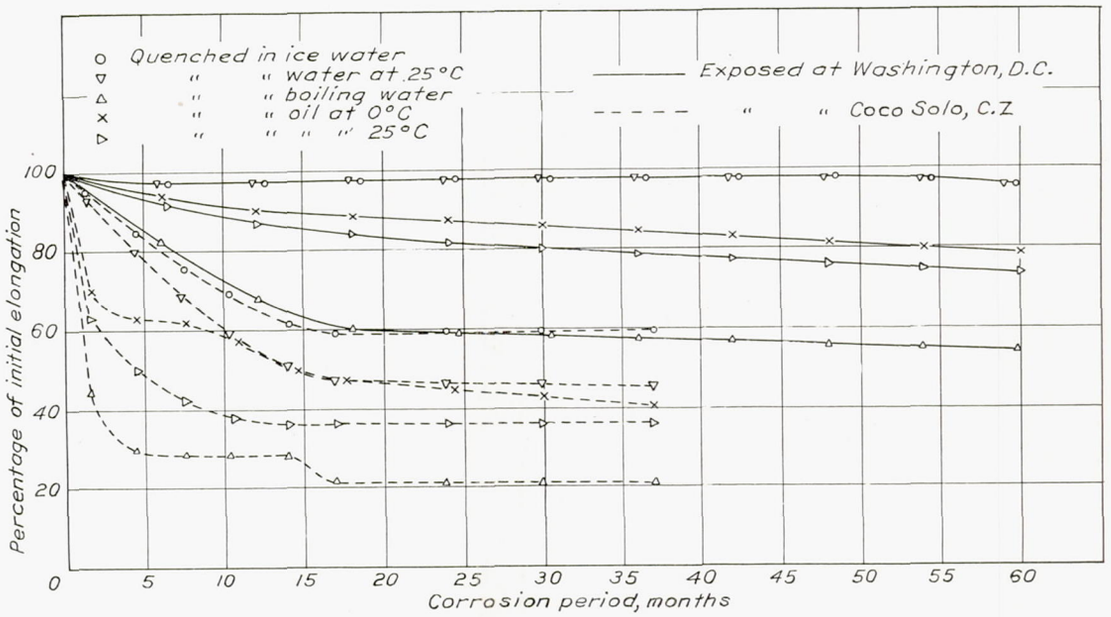



FIGURE 7.—Effect of rate of quenching upon the resistance of duralumin to corrosion. All specimens given a solution heat treatment 15 minutes at 505° C.

The attack shown in figure 8d, although strongly suggestive of a coarsely intercrystalline trend, differs markedly in appearance from the typical intercrystalline attack pictured in figure 8a. It is characterized, particularly in its earlier stages, by the relatively greater width of the attacked intercrystalline areas, and by the relative frequency of pits beneath areas so attacked. It appears to represent a stage of attack intermediate between the two distinctive types and, like "pock-form" corrosion, its occurrence is limited in duralumin to material heat treated by a few of the less commonly used methods.

Although the various types of attack described above are readily distinguishable under the microscope, they are not usually determinable from a macro-examination of the surface, aside from the "pock-form" corrosion already noted. Thus, the specimens shown in figure 9c and d are quite similar in aspect despite the predominate presence of intercrystalline attack in d and

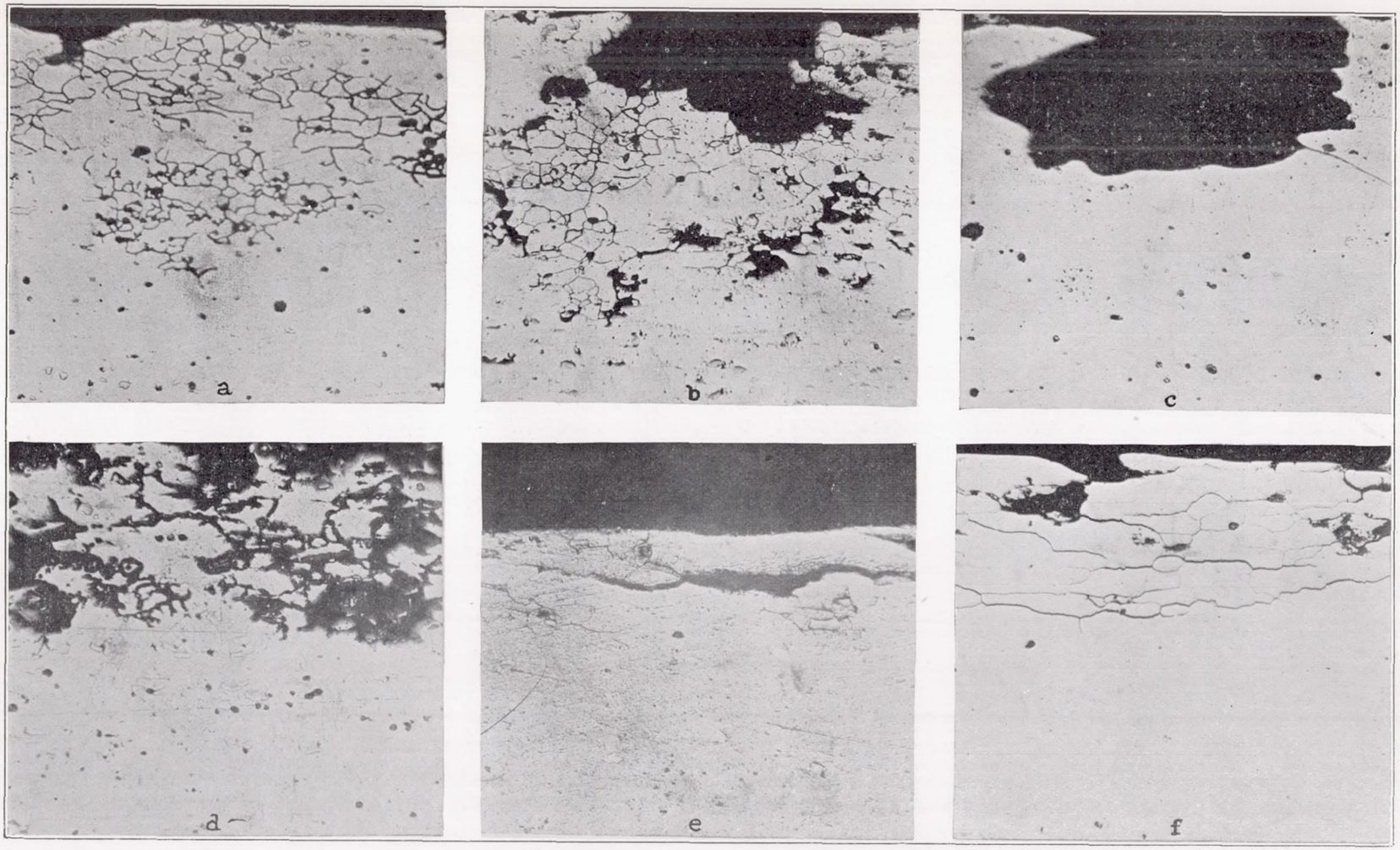



FIGURE 8.—Characteristic microstructural appearances of corrosive attack on polished duralumin specimens. (a) Typical intercrystalline attack; (b) typical intercrystalline attack with an accompanying pit, which presumably resulted from the removal of loosened grains; (c) typical pitting attack; (d) coarsely intercrystalline or "intermediate" attack; (e) and (f) "pock-form" corrosion. ×250.

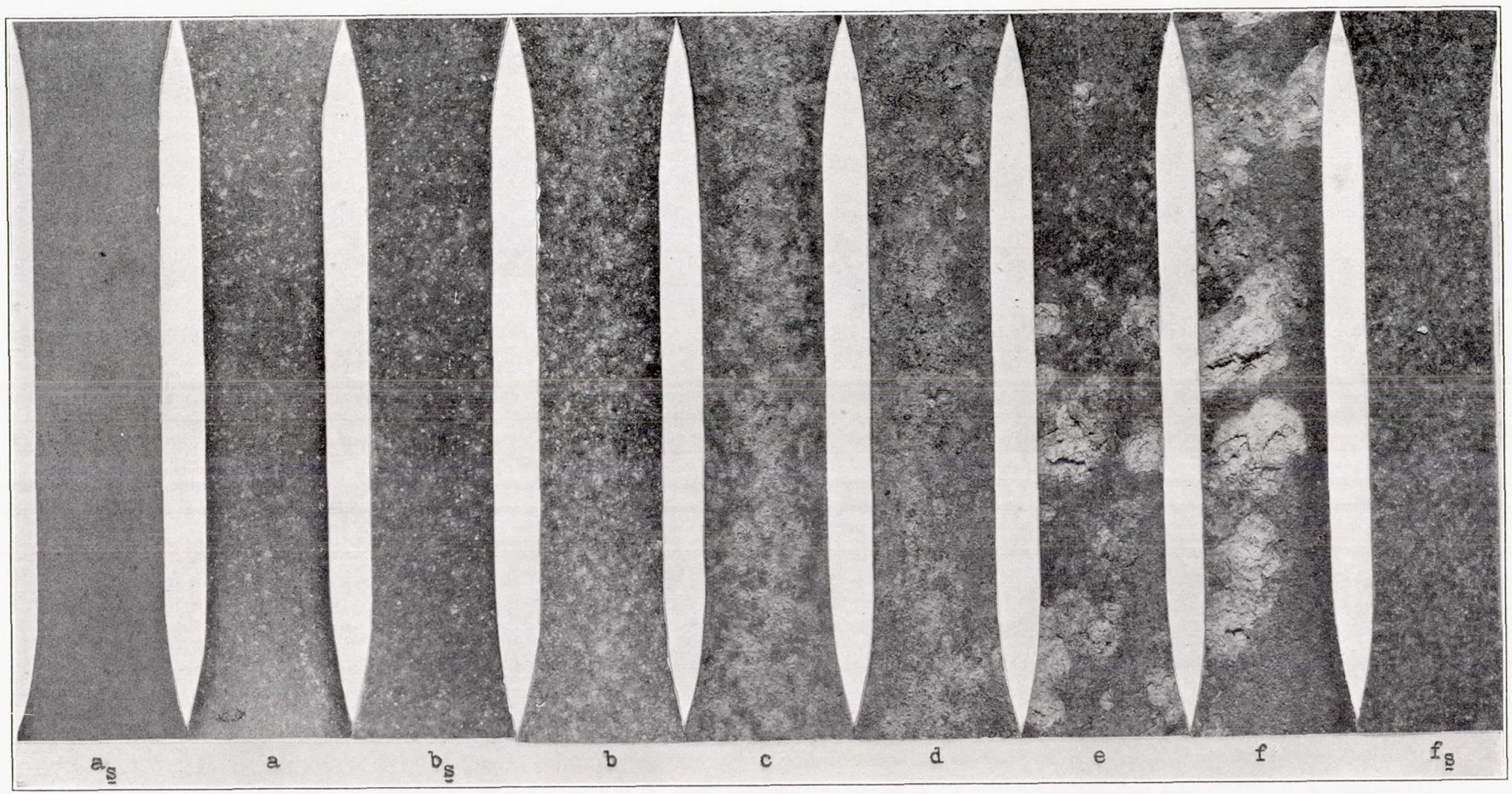



FIGURE 9.—Surface appearance of duralumin specimens exposed to the weather. Specimens were solution heat treated, quenched in ice water and aged at room temperature unless otherwise noted. (a) 5 years at Washington; (b) 5 years at Hampton Roads; (c) 3½ years at Coco Solo; (d) quenched in boiling water, 3½ years at Coco Solo; (e) artificially aged for 3 hours at 150° C., 2 years at Hampton Roads; (f) aged 96 hours at room temperature and reheated 5 hours at 135° C., 5 years at Hampton Roads. Skyward surfaces are designated s. Note the differences in the amount of the accumulated corrosion products, depending upon the locality of exposure and the position of the surfaces relative to the sky. "Pock-form" corrosion is present on (e) and (f). ×1.

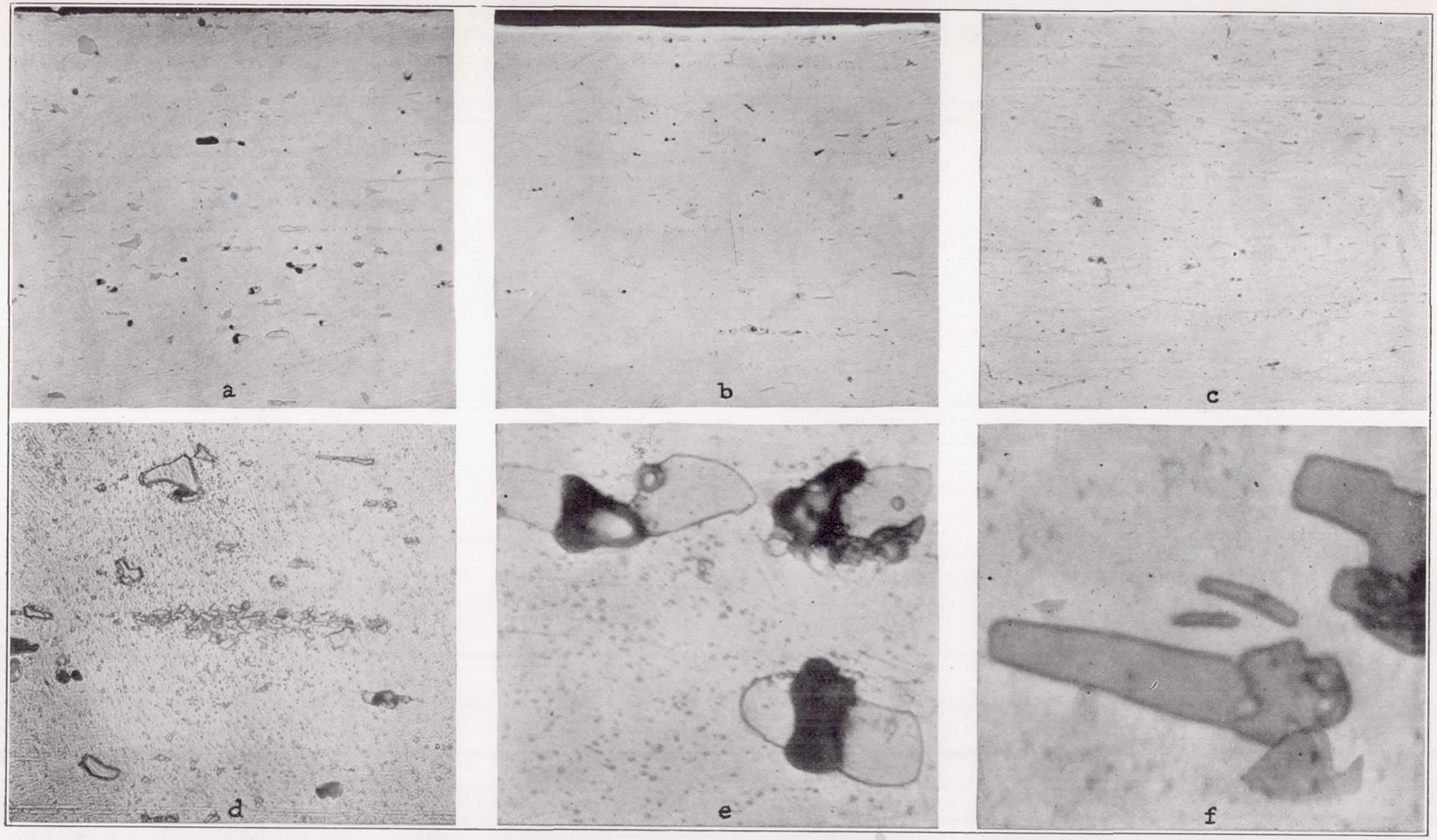



FIGURE 10.—Longitudinal sections of different wrought-aluminum alloys in the quenched and aged condition of heat treatment. The differences in microstructure are relatively minor ones dependent upon the amount, size, and distribution of the precipitated constituents. Note the complex association of other constituents with the lighter colored $CuAl_2$, visible at high magnifications. (a) Alloy 17S, ×250; (b) alloy A17S, ×250; (c) alloy 51S, ×250; (d) alloy 17S, ×500; (e) alloy I–2, ×2,000; (f) alloy 63A, ×5,000. (a) to (c) were unetched: (d) to (f) were etched in a 1 percent hydrofluoric acid solution.

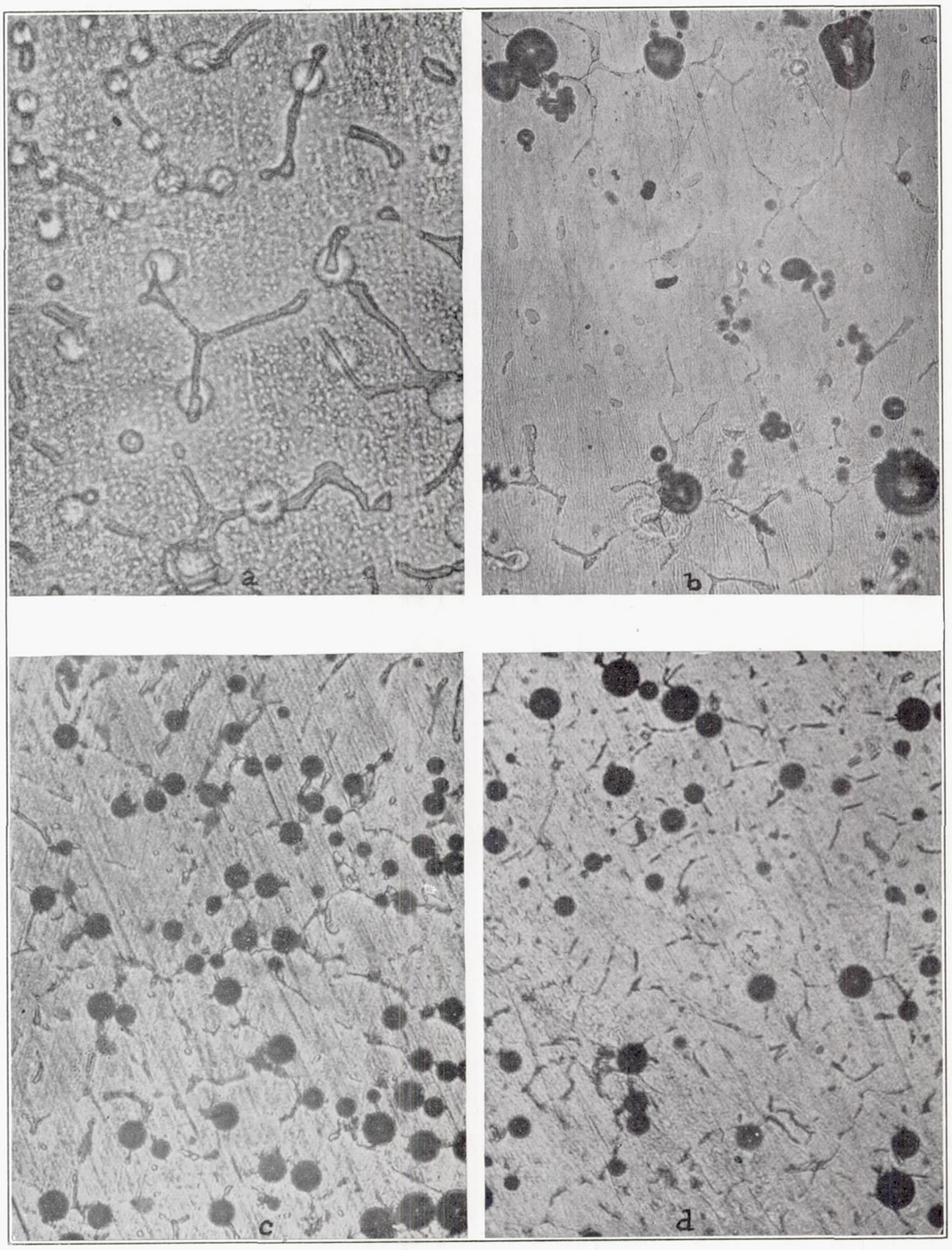



FIGURE 11.—Cast materials, the surfaces of which were covered with glycerin to trap the bubbles of hydrogen generated from the action of the corroding medium. Note how, in all cases, the bubbles are associated with the network of constituents. The materials and corroding agents were: (a) Alloy 17S, sodium hydroxide; (b) alloy 17S, ammonium chloride plus hydrogen peroxide; (c) alloy 25S, hydrofluoric acid; (d) alloy 51S, hydrofluoric acid. ×250.

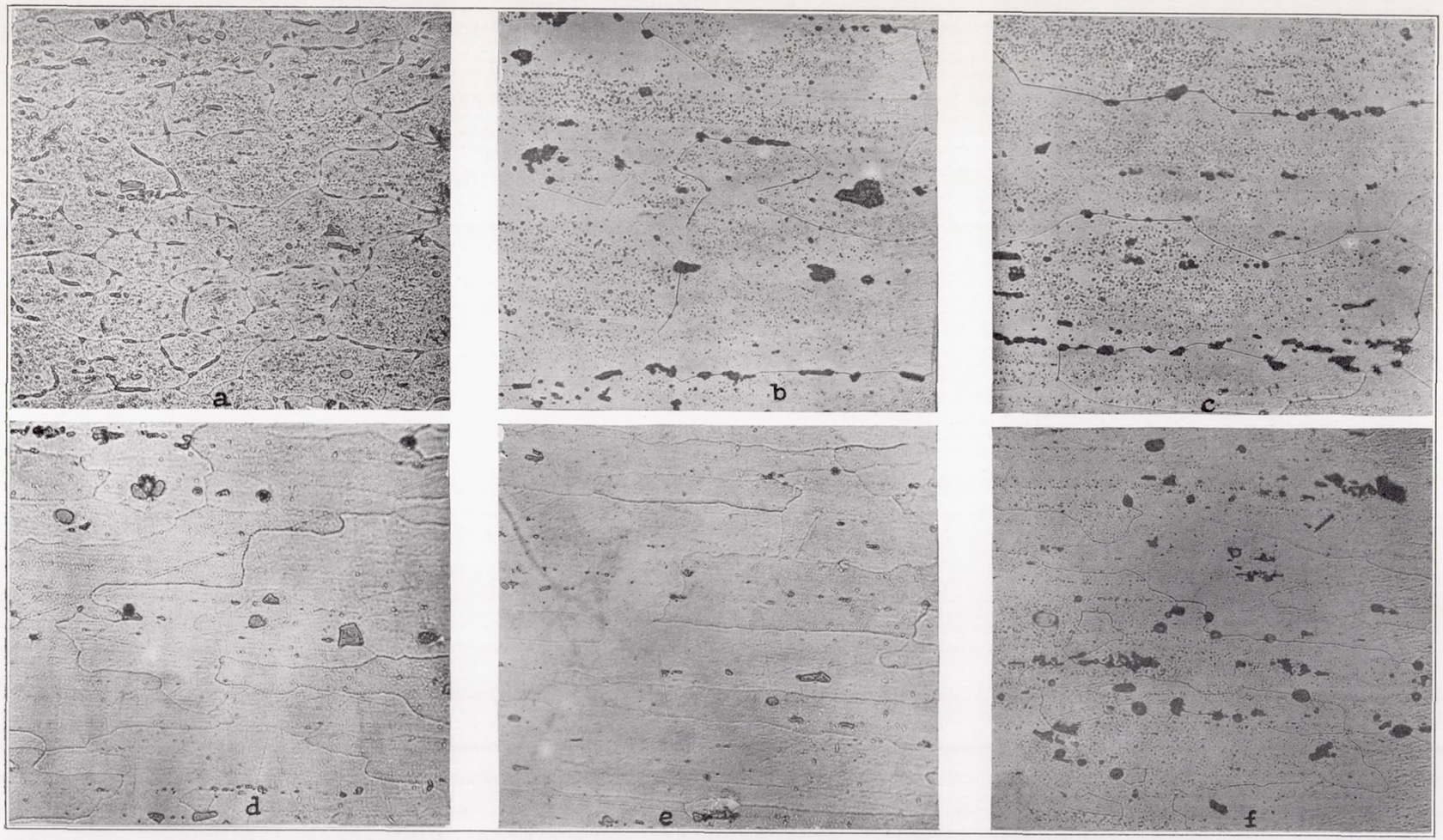



FIGURE 12.—Longitudinal sections of duralumin specimens cooled at different rates after solution heat treatment for 2 hours at 505° C. Quenchants were: (a) Cooled with the furnace; (b) water at 100° C.; (c) oil at 25° C.; (d) water at 25° C.; (e) water at 2° C.; (f) water at 2° C. Aged at room temperatures, except (f) which was artificially aged, immediately after quenching, for 5 hours at 135° C. The presence of constituents at the grain boundaries, and also as a fine "pepper" within the grains, is noticeable in specimens quenched in hot water or cold oil. Quenching in cold water, however, resulted in the retention of most of the constituents in solution, after aging: the structure is, in contrast, "clean." Reheating of material quenched in cold water resulted in additional precipitation. Etched in 1 percent hydrofluoric acid. ×250.

its absence in c. Specimens containing intercrystalline attack, however, after being tested in tension, frequently exhibited a characteristic "crazed" appearance (fig. 24d) indicative of embrittlement.

### CAUSES OF INTERCRYSTALLINE ATTACK

Duralumin, structurally, consists of a matrix of an aluminum-rich solid solution throughout which are disseminated particles of harder constituents, principally $CuAl_2$ and iron-magnesium-manganese-silicon bearing constituents. In addition to the particles which are readily visible under the microscope, there is good reason for believing that there are other submicroscopic particles which may originate by precipitation from solid solution during the aging operation and to which the alloy may owe its superior strength and hardness.

Since the majority of the wrought-aluminum alloys consist essentially of an aluminum-rich solid solution, the size and distribution of the precipitated constituents afford one of the principal means of differentiation of the alloys under the microscope. Such differences are usually less marked between heat-treated alloys of dissimilar chemical composition, than between any one alloy in its cast and wrought condition. The differences involved are apparent from a comparison of figure 10a, b, and c with each other and then with figure 11.

Experiments were performed to determine whether or not microstructural changes in wrought duralumin, resulting from various heat treatments, could be correlated with the tendency toward the development of the intercrystalline attack. The frequent appearance upon the surface of specimens corroded in the laboratory of a reddish-brown deposit, containing copper, suggested that the copper-bearing constituent, $CuAl_2$, might be intimately associated with corrosion phenomena in duralumin.

In order to obtain confirmatory evidence, observations were made upon the polished surfaces of a few duralumin-type alloys, in the cast condition, while they were being subjected to attack by a corrosive reagent. Corrosive attack of aluminum and aluminum-rich alloys results in the liberation of hydrogen. In order to hold the bubbles of gas *in situ* and so reveal where the corrosive attack was most intense, the polished section of the specimen, after momentary dipping in the reagent, was covered with glycerine. The tests confirmed previous evidence in revealing positively preferential attack on the constituents. Examples of this method are illustrated in figure 11.

Microscopic examination on slightly etched specimens demonstrated quite conclusively that in duralumin quenched in hot water or cold oil, there was a distinct tendency for the precipitation of the $CuAl_2$ throughout the grains and for the coalescence of constituents along the grain boundaries. This distribution was found also to prevail in annealed material, but *not* in specimens quenched in cold water. Differences in microstructure of this kind are exemplified in figure 12. The specimens pictured in a, b, c, and f of figure 12 developed intercrystalline attack in less than 5 hours in intermittent-immersion tests in the chloride-peroxide reagent, whereas such attack was not present in d and e at the conclusion of the test period of 80 days.

The evidence accumulated in the present investigation all points to the coalescence of the $CuAl_2$ and associated constituents at the grain boundaries as a very important cause for the susceptibility of duralumin to intercrystalline attack. For example, no duralumin specimen, quenched in cold water from a solution heat treatment temperature of 500° C., and aged at room temperature, developed intercrystalline attack in either laboratory tests in various corrosive mediums, or in the weather-exposure tests. On the other hand, the intercrystalline attack was found on every specimen quenched in cold oil or hot water. These facts support the conclusion that the tendency toward an intercrystalline attack when corroded may be inherent in duralumin under specific conditions of heat treatment and not so under others.

It is not to be inferred that the actual mechanism of intercrystalline corrosion is amenable to as simple a partial explanation as the foregoing might seem to imply. The potential relationships involved in the corrosion of duralumin are exceedingly complex, and not at present entirely comprehended. Microscopic evidence, for example, reveals the $CuAl_2$ constituent to be often surrounded by a sheath (fig. 10f), probably of a complex eutectic, the composition of which remains unknown and which conceivably might be the constituent attacked in the process of corrosion. Often, too, the $CuAl_2$ occurs intimately associated with other constituents (fig. 10e). The fact remains, however, that the distribution of the $CuAl_2$ constituent probably plays the determining rôle, in duralumin.

This does not necessarily imply that intercrystalline corrosion will not develop under specific conditions in cold-water-quenched duralumin. The subsequent reheating of such material at elevated temperatures may induce coalescence of constituents at the grain boundaries (fig. 12f). It is possible that under corrosive conditions in which there is a deficiency of oxygen, or the application of certain unusual types of external stresses, intercrystalline attack might develop for reasons other than the distribution of microstructural constituents.

It has been observed, in intermittent-immersion laboratory corrosion tests in the chloride-peroxide reagent, that the effect of stress was, in general, to intensify the rate of corrosive attack and not to influence its type materially. This applies to specimens,

stressed either in static tension or alternately by flexure (reference 6), with the stresses frequently in the neighborhood of the "yield point."

The view entertained by certain European metallurgists, that internal stresses may be the prime cause of intercrystalline attack in aluminum alloys, has not been corroborated here in the case of duralumin. The known susceptibility of annealed wrought duralumin to intercrystalline attack is in itself in opposition to this hypothesis. Opinions considered in the past that certain mediums, such as salt solutions, might be the prime cause for the development of intercrystalline attack, can also no longer be regarded as tenable.

### RATE OF PENETRATION OF CORROSIVE ATTACK

The maximum depth of corrosive attack was determined on all specimens exposed to the weather. The results obtained on duralumin quenched in ice water and in boiling water are represented graphically in figure 13. The following conclusions are supported by the data: (1) For a given period of time the intercrystalline attack penetrates much more deeply than does pitting, which tends to widen rather than deepen; (2) the depth of both types of attack is a function of the conditions of exposure, being appreciably greater in the presence than in the absence of saline conditions for the same length of time; (3) the rate of penetration of both types of attack is highest during the early periods of exposure, the initial period of accelerated attack being followed by one of more or less complete cessation or arrest over a prolonged period. These conclusions, of course, apply only in the absence of stresses acting simultaneously with corrosion.

The foregoing affords an explanation for a fact frequently observed in practice, that the tensile properties of duralumin corroded in an intercrystalline fashion are appreciably lower than those of similar material which, after service for the same length of time, shows only the pitting type of attack.

The presence or absence of saline conditions may be regarded as a vital factor in determining the rate of corrosion during the initial period of accelerated attack. In the absence of such conditions as, for example, at Washington, the initial period of accelerated attack on "properly" heat-treated materials, seldom resulted in attack (pitting) exceeding 0.002 inch in depth; the resulting loss in physical properties was insufficient to lower the elongation much below 95 percent of its initial value (fig. 7). In the presence of saline conditions, as at Coco Solo and Hampton Roads, an initial arrest on cold-water-quenched materials occurred when the percentage of the initial elonga-

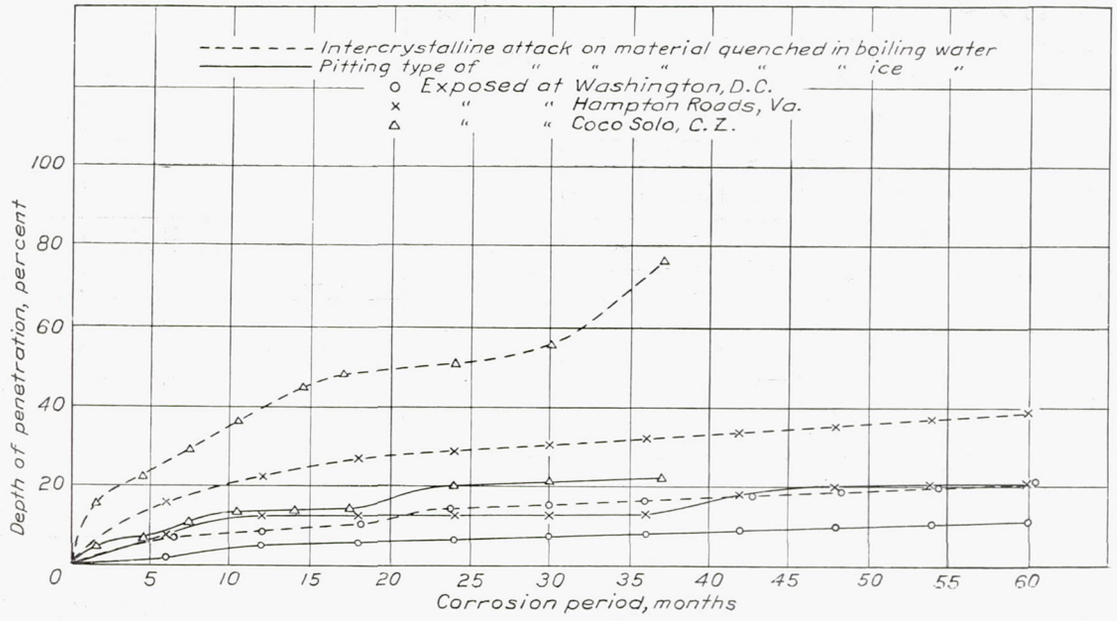



FIGURE 13.—Effect of locality upon penetration of corrosive attack in duralumin (178).

NOTE.—Material 0.064-inch thick. Values plotted are double that of the maximum depth of attack measured on one surface.

tion approximated 65 and the corresponding depth of penetration of attack was between 0.003 and 0.004 inch.

The differences were much more pronounced on duralumin specimens heat-treated "improperly", as by quenching in boiling water (fig. 13). At Washington the most rapid rate of penetration of intercrystalline attack occurred within the first 6 months, reaching a depth of approximately 0.004 inch. During the remainder of the 4½-year-exposure period the depth increased only to 0.006 inch. The elongation decreased within 18 months to approximately 65 percent of its initial value, and then fell off very slowly to about 55 percent at the conclusion of the test period (fig. 7).

At Coco Solo, however, the intercrystalline attack penetrated very rapidly during the first 6 months and reached a depth of about 0.007 inch. The elongation decreased to approximately 20 percent of its initial

value. The lower elongation obtained for nearly identical maximum depths of intercrystalline attack may be attributed, at least in part, to the much greater number of areas of attack in a unit of surface area at Coco Solo than at Washington. Less accelerated penetration occurred at Coco Solo to the conclusion of the 37-month-exposure period, at which time the maximum depth of attack approximated 0.024 inch. Hence, if both sides of the 0.064-inch-thick sheet were attacked to the same degree, penetration after 37 months would amount to 80 percent of the thickness.

An important feature in the corrosion of the aluminum alloy sheet materials, the variation in the rate of attack, is to be noted in figure 13 and is in practically constant evidence in all the figures illustrating the effects of corrosion on the ductility. It is apparent that corrosion at a particular locality did not result in a progressive lowering of the tensile properties or increase in depth of attack in proportion to the period of exposure. The major loss, without exception, was found to occur within the first 18 months of exposure to the weather, and usually within the first 6 months. An arrest or relatively very slow attack followed, during which the ductility and penetration values remained practically unchanged to the conclusion of the 5-year-test period. It cannot be presumed, however, that such an arrest would occur on sheet material highly stressed in service. There is some evidence to indicate that localized high stresses at the base of corroded areas render them more susceptible to further corrosion.

This tendency toward arrest after an initial period of accelerated attack has been noted by other investigators (reference 13) and in metals other than aluminum alloys. It has been attributed to the formation of a protective oxide film or to the protective effect of accumulated products formed as a result of corrosion. The existence of this period of practical cessation of attack in aluminum alloys is of importance with respect to their permanence in service. Particularly is this so on sheet material, where corrosion is equivalent, in effect, to an appreciable reduction in thickness.

The knowledge that corrosion may practically cease after a time, and that the physical properties may remain practically unchanged for a period of years thereafter, is reassuring. But it is highly improbable that the arrest period continues indefinitely. The evidence in the present investigation merely confirms the existence of an arrest period and demonstrates that it endures for at least 4 years on correctly

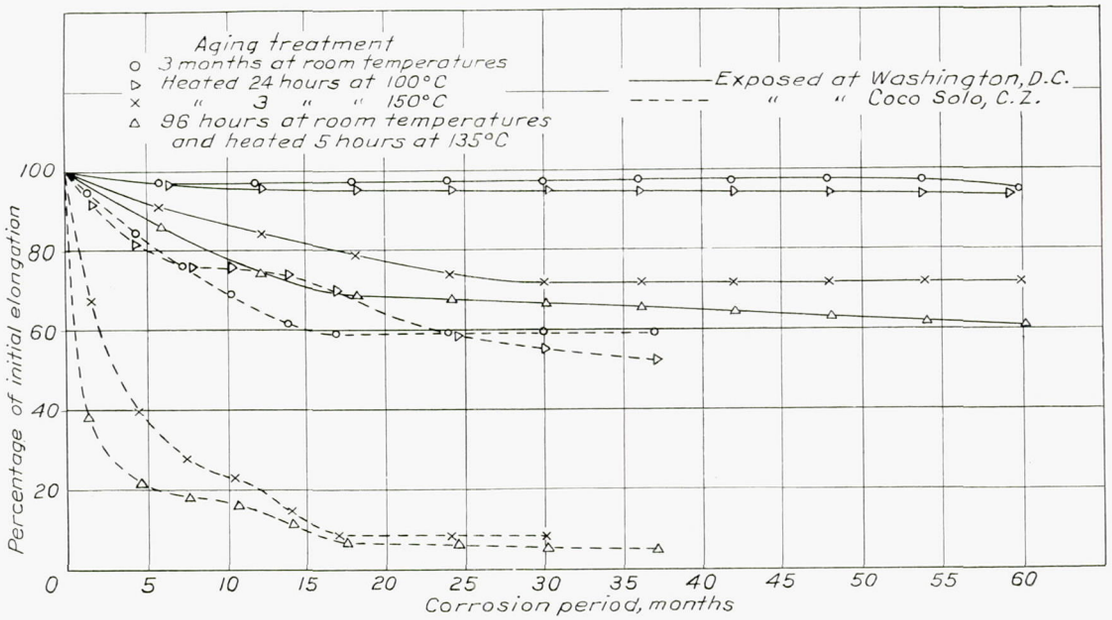



FIGURE 14.—Effect of conditions of "aging" upon the resistance of duralumin to corrosion. All specimens given a solution heat treatment 15 minutes at 505° C. and quenched in ice water.

heat-treated, 14-gage sheet-aluminum alloys exposed, in the absence of stresses, under relatively severe conditions.

It is conceivable that the arrest period may be followed by one or more stages of accelerated attack and arrest. Such a possibility is suggested, in fact, by a few of the curves depicting the behavior of materials prone to intercrystalline attack and exposed under marine conditions (figs. 7, 13, and 26).

### CONDITIONS OF AGING

The phenonenon of hardening, or aging, which occurs at room temperature in duralumin rapidly cooled from the solution heat treatment temperature, is regarded by most authorities (references 14 and 15) as the result of precipitation of submicroscopic constituents from the solid solution matrix. The process is frequently designated as "precipitation hardening."

More or less complete hardening takes place in quenched duralumin within a week, the greater part of which occurs within the first 48 hours. The process can be accelerated by heating for relatively short periods at slightly elevated temperatures, which is termed "artificial aging."

Laboratory tests (reference 3) indicated that duralumin quenched in ice water and immediately aged artificially at 100°, 135°, 200° or 285° C. was rendered susceptible to the intercrystalline type of corrosive attack. Maximum susceptibility was observed when aging was carried out at 135° C., material so treated being even more susceptible to corrosive attack than duralumin quenched in boiling water but aged in the ordinary manner. It is of interest to observe that the type of attack present on duralumin aged at 285° C. closely resembled that illustrated in figure 8d.

The evidence indicated that susceptibility to intercrystalline attack had its inception at about 100° C. and that the period of heating might on occasions be a determining factor. Specimens aged in an electric resistance furnace for a period of 7 hours at 100° C. developed only the pitting type of attack when subsequently corroded in a chloride solution, whereas specimens aged similarly for 24 hours developed intercrystalline attack. On the other hand, specimens aged in a steam bath for 24 hours at 100° C. did not exhibit intercrystalline corrosion.

The effect of reheating quenched-and-aged duralumin was found to be much the same as when the heating was performed immediately after quenching following solution heat treatment. Hence, the application to sheet duralumin of protective coatings which require "baking" at an elevated temperature is inadvisable. The changes in microstructure resulting from reheating were difficult to interpret. At those temperatures which made for extreme susceptibility of corrosive attack, however, there was noticeable a tendency (fig. 12f) for constituents to precipitate from the solid solution and to coalesce.

The results of weather-exposure tests at Washington and Coco Solo, of duralumin aged in various manners, are given in figure 14. All the specimens were quenched in ice water after the solution heat treatment. It will be noted that specimens aged 24 hours at 100° C. (in steam) behaved similarly, in the matter of loss in ductility, to those aged at room temperature. Specimens aged at 135° or 150° C. resembled each other in behavior, but were appreciably inferior to the ones aged at the lower temperatures. It is apparent from figure 14 that duralumin sheet aged at the two highest temperatures might be rendered unfit for service in less than 2 months at Coco Solo. At both Hampton Roads and Coco Solo intercrystalline corrosion penetrated the specimens with unusual rapidity. Surface layers frequently fell from the sheet and, in general, the surface appearance of these specimens was far worse than that of any others exposed to the weather (fig. 9e and f).

The results in the present investigation are in close agreement with those independently obtained with a "super-duralumin" by Meissner (reference 12), who found the temperature range of 135° to 150° C. for artificial aging to favor maximum susceptibility to corrosive attack. This was true irrespective of the rate of cooling following the solution heat treatment or following the precipitation hardening treatment.

Some aluminum alloys require artificial aging treatments for the attainment of maximum physical properties as, for example, the alloys commercially designated as 25S and 51S. It so happens that the recommended treatment involves heating for periods of from 8 to 17 hours at about 140° C. for alloy 25S and about 160° C. for alloy 51S. Both the laboratory and weather-exposure tests indicated that these alloys are much more susceptible to corrosive attack in the artificially aged condition than when aged at room temperatures. However, their use has been more or less restricted to massive forgings such as propellers. Inasmuch as corrosion phenomena are confined to surface action, the factor of corrosion becomes an increasingly negligible one as the thickness of the metal section is increased, with the exception of parts subjected to repeated fluctuations of stress.

Figure 15 will serve to illustrate indirectly the effect of artificial aging upon the corrosion resistance of alloy 25S in sheet form. Specimens so aged, despite the subsequent applications of surface protective coatings prior to exposure, exhibited a relatively rapid loss in ductility with accompanying intercrystalline attack. The sets designated in figure 15 as artificially aged were exposed in the condition of heat treatment as performed by the manufacturer. Incidentally, the "chromium varnish" coating applied to these specimens failed completely to afford protection, as revealed by visual macro-examination, after less than a year at Washington and less than 6 months at Hampton Roads and Coco Solo. Reference to figure 28g will illustrate that the surface appearance of the corroded sheet was uniformly poor.

The aluminum-pigmented spar varnish coating, applied on an oxidized surface, however, showed little visible evidences of failure at the conclusion of the maximum exposure periods at any of the localities. The curves illustrate that lack of visible evidence of failure on the paint coating does not necessarily signify that moisture may not have penetrated the protective coating and caused corrosion and loss in tensile properties.

### COLD-WORKING AFTER VARYING AGING INTERVALS

A few sets of specimens of 17S alloy were included in the weather-exposure program to determine the

relative corrosion resistance of duralumin specimens given various periods of aging at room temperatures and then cold-worked equivalent amounts. The section at both ends. The average initial tensile properties of the specimens, cold-worked as above, are given in table III.

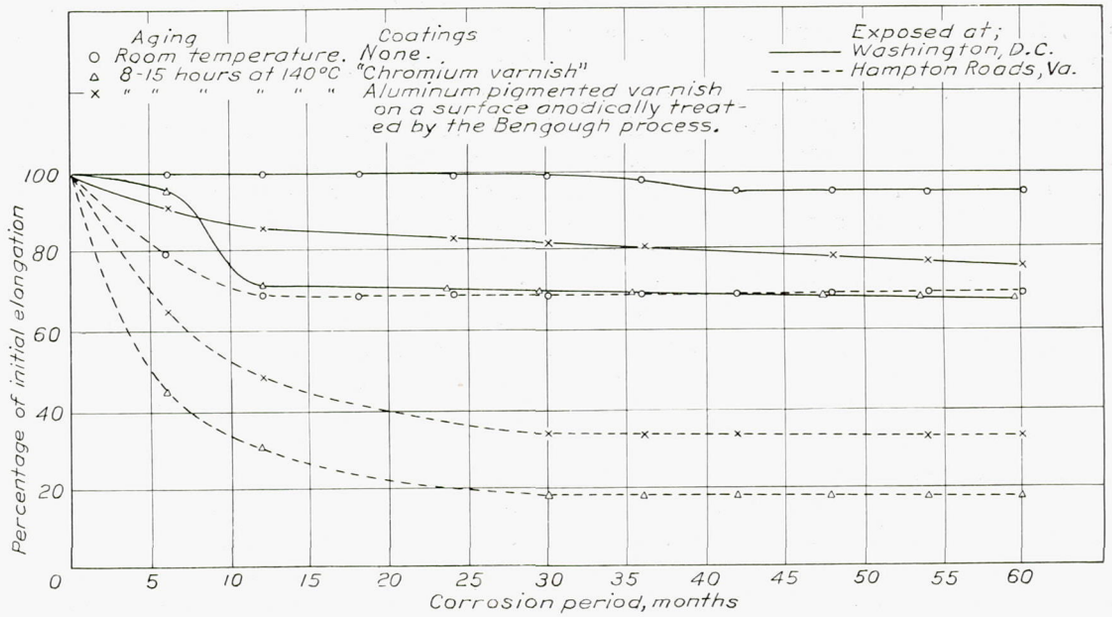



FIGURE 15.—Effects of "aging" and protective coatings upon the resistance of alloy 25S to corrosion. All specimens solution heat treated at 520° C. and quenched in cold water. Specimens aged at the higher temperature were alloy 25ST commercially treated.

treatments are summarized in figure 16, together with the results at Washington and Hampton Roads. Cold-working by stretching was accomplished in a

It will be noted from figure 16 that the aging period prior to cold-working was for all practical purposes immaterial for specimens quenched in cold water.

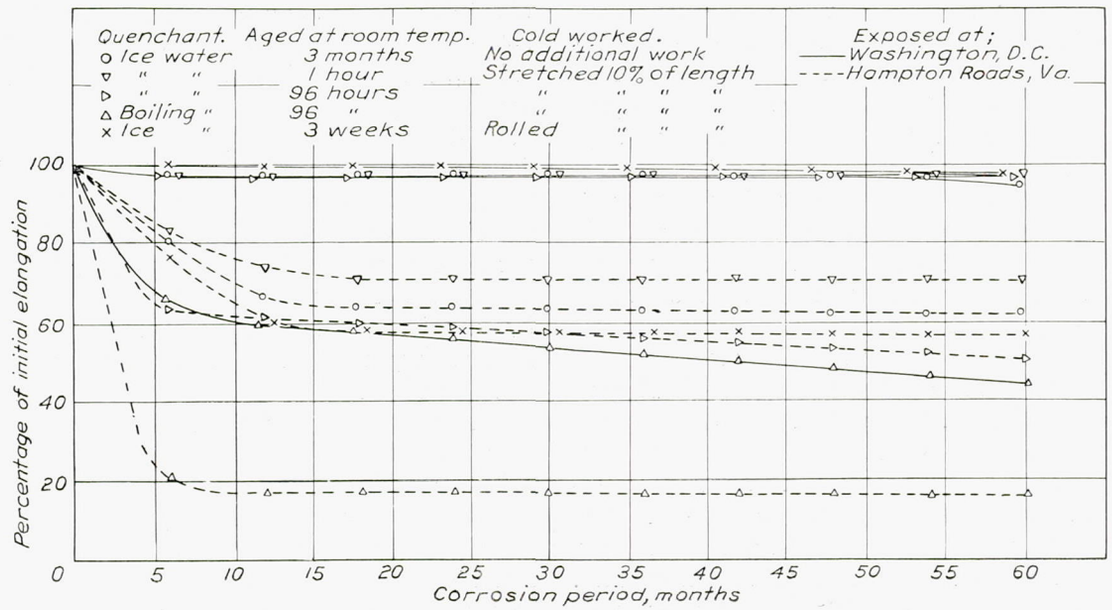



FIGURE 16.—Effect of cold-working and "aging" upon the resistance of duralumin to corrosion. All specimens given a solution heat treatment 15 minutes at 505° C.

tensile-testing machine, the 10-percent stretch being determined over a 2-inch gage length on the reduced section. The 10-percent increase in length of the cold-rolled specimens was measured over a 5-inch gage length, which extended slightly beyond the reduced

Specimens given the intermediate aging period of 96 hours appeared somewhat inferior in corrosion resistance to those aged only 1 hour or to those aged 3 weeks or more, but the difference was not great. That the method of quenching played a more important rôle

than did the subsequent aging period is evident from the rapid loss in ductility, at both localities, of specimens quenched in boiling water.

In the specimens given the 1-hour aging periods, there were some indications of additional age-hardening after cold-working, which may account for the difference in behavior of specimens of this set as compared with the others. The corrosive attack was predominantly of the pitting type, except on a few of the specimens exposed at Washington and the first three withdrawn at Hampton Roads; on these the intermediate type (fig. 8d) was occasionally in evidence. Intercrystalline attack was found only on specimens

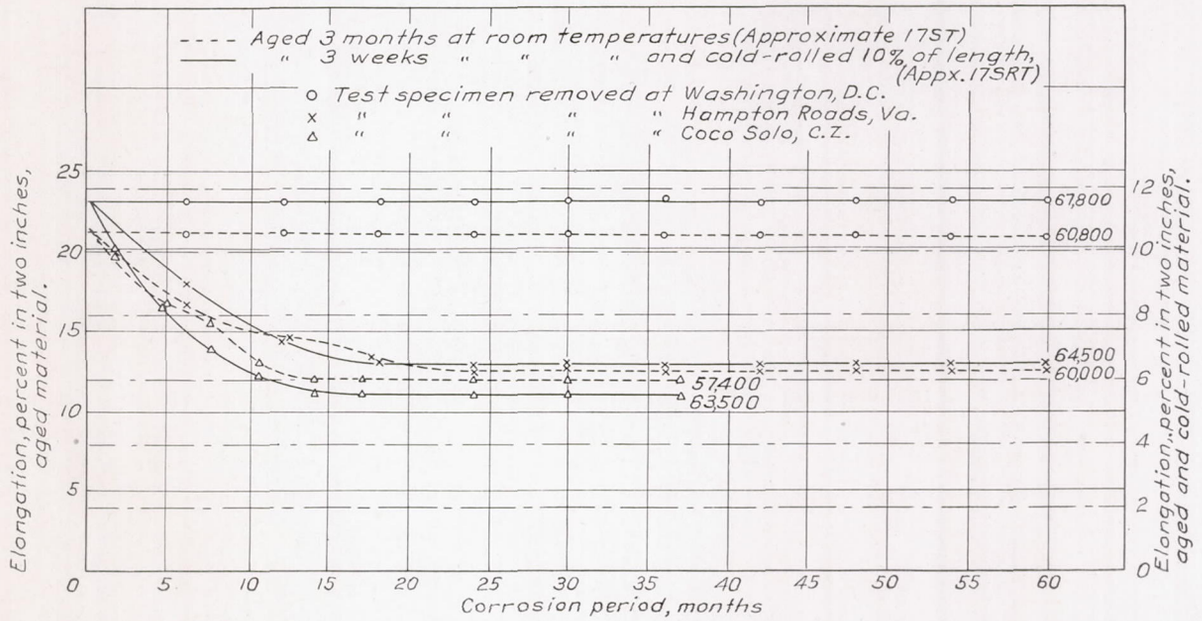



FIGURE 17.—Effect of weather exposure upon 14-gage sheet duralumin (17S). All specimens given a solution heat treatment 15 minutes at 505° C. Figures at ends of curves are average U.T.S. values of all specimens on the horizontal section of the curve.

of the set which was quenched in boiling water prior to cold-working.

The weather-exposure tests would indicate that cold-working of material quenched in boiling water resulted in acceleration of corrosive attack, which induced a more rapid loss in ductility during the first year than occurred in the absence of cold-working. For periods of exposure in excess of a year, however, the tensile properties of the specimens were practically the same, irrespective of the initial cold-working. Compare, for example, the sets quenched in boiling water and exposed at Washington (figs. 7 and 16). Cold-working of properly heat-treated and aged duralumin did not materially affect its corrosion resistance (fig. 17).

#### TEMPERATURE AND DURATION OF SOLUTION HEAT TREATMENT

At the time that this investigation was begun some metallurgists advocated solution heat treatment of duralumin at 425° C. for a prolonged time, in preference to shorter periods at the usual temperature of 505° C. Laboratory tests (reference 3) showed that quenching from a temperature of 425° C. resulted in appreciably lower tensile properties, even though the heating was prolonged as much as 8 hours. It was apparent that the temperature was too low to effect complete solution of the alloy constituents. After a 3-month period of age-hardening the ultimate tensile strength was approximately 47,000 pounds per square inch, and the average elongation about 19 percent (table III). The ultimate tensile strength and elongation of duralumin heated at 505° C., and quenched and aged, averaged approximately 62,200 pounds per square inch and 20.7 percent, respectively. This is reason sufficient to discourage the use of the lower solution heat treatment temperature. Both laboratory and weather-exposure tests demonstrated, moreover, that the corrosion resistance of material quenched from 425° C. was somewhat inferior to that quenched from 505° C., which further removes the former treatment from practical consideration. The results from the weather-exposure tests are shown in figure 18.

Typical intercrystalline attack was not in evidence on any of the specimens quenched from 425° C., the predominating type of attack on specimens heated for a period of less than 4 hours being that of figure 8d. Longer heating periods appeared to result in some slight improvement in corrosion resistance and the attack present was invariably that of the pitting type. The exposure-test results also revealed no practical difference in the corrosion behavior of duralumin sheet heated for 15 or for 60 minutes at 505° C. prior to quenching (fig. 18).

### CHEMICAL COMPOSITION

Previous laboratory tests (reference 2) on aluminum alloys of varying chemical compositions led to the tentative conclusion that, of the elements usually present, copper is most closely related to the susceptibility to corrosion. The results of the weather-exposure tests on the same alloys are given graphically in figures 19, 20, and 21. Inasmuch as these alloys varied appreciably with respect to their physical properties, the actual data obtained are given in detail in table II. All the alloys exposed to the weather were quenched in ice water, after a 15-minute solution heat treatment, and allowed to age at room temperature. The solution heat treatment temperature was 505° C. for all the alloys except 25S and 51S, for which 520° C. was used.

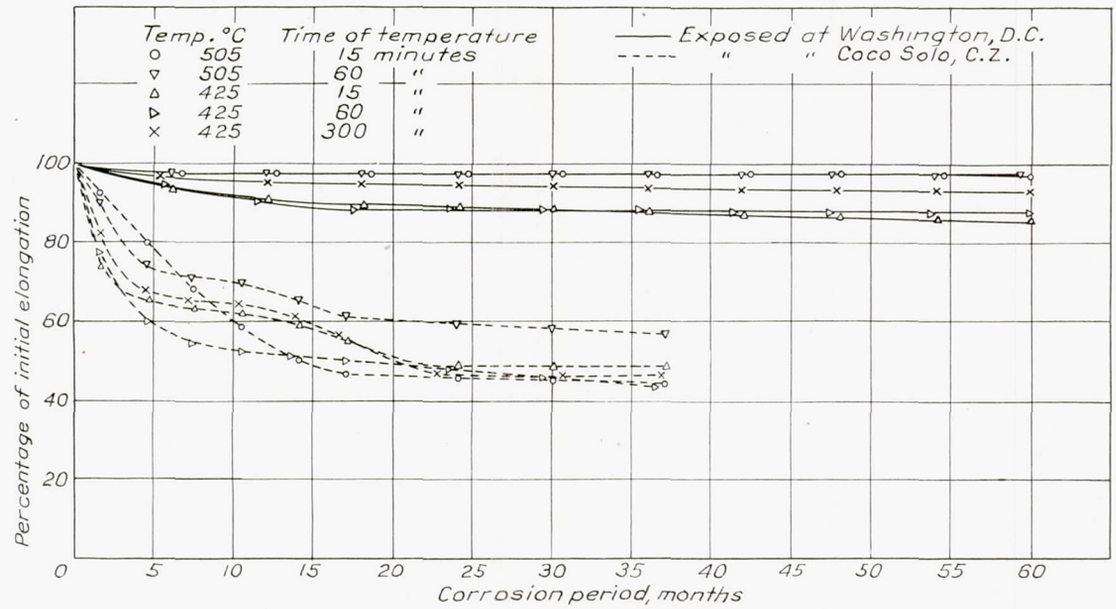



FIGURE 18.—Effect of temperature and time of solution heat treatment upon the resistance of duralumin to corrosion. All specimens quenched in water at 25° C. and aged 3 months at room temperatures.

It will be noted from figure 19 that the corrosion resistance of all the alloys, when exposed at Washington, was uniformly excellent. The percent of the initial elongation was more than 80 at the end of the 5-year exposure period. For all practical purposes, their corrosion resistance can be regarded as about the same for the period covered by the tests.

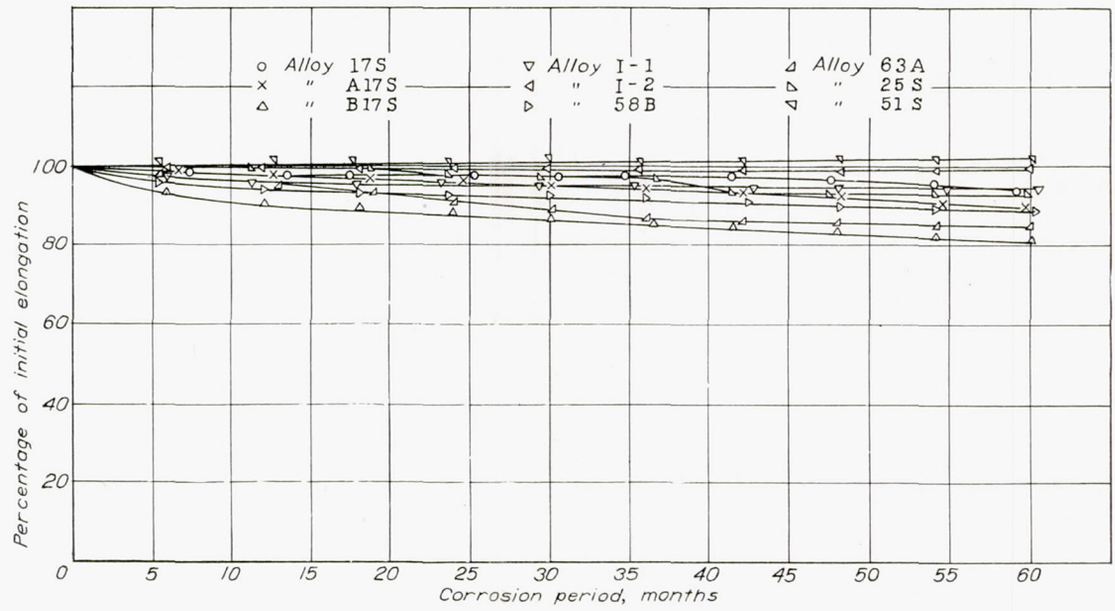



FIGURE 19.—Effect of chemical composition upon the corrosion of aluminum alloys exposed at Washington. All specimens solution heat-treated, quenched in ice water, and aged 3 months at room temperatures.

It may be seen from figures 20 and 21 that the behavior of the alloys, whether exposed at Coco Solo or at

Hampton Roads, was quite similar, with corrosion tending to result in somewhat lower physical properties at the former locality. The consistently higher values obtained on specimens of alloy I–2, A17S, and 58B would indicate that the use of high purity materials and lower copper contents does appreciably increase the resistance of duralumin to corrosion. The consistently lower values obtained on specimens of alloy 63A, on the other hand, may be taken as indicative that relatively high iron contents tend toward inferior corrosion resistance.

The order in which the materials arranged themselves, during the first year, in sequence of increasing susceptibility to corrosion as based on the ductility values, was practically the same at both localities. However, there was sufficient scatter within the specimens of any given set, or alloy, as to make any rigid classification extremely dubious. Practically all of the alloys, after the maximum exposure period at each locality, had ductility values higher than 55, which indicates that there were no appreciable losses in tensile strength.

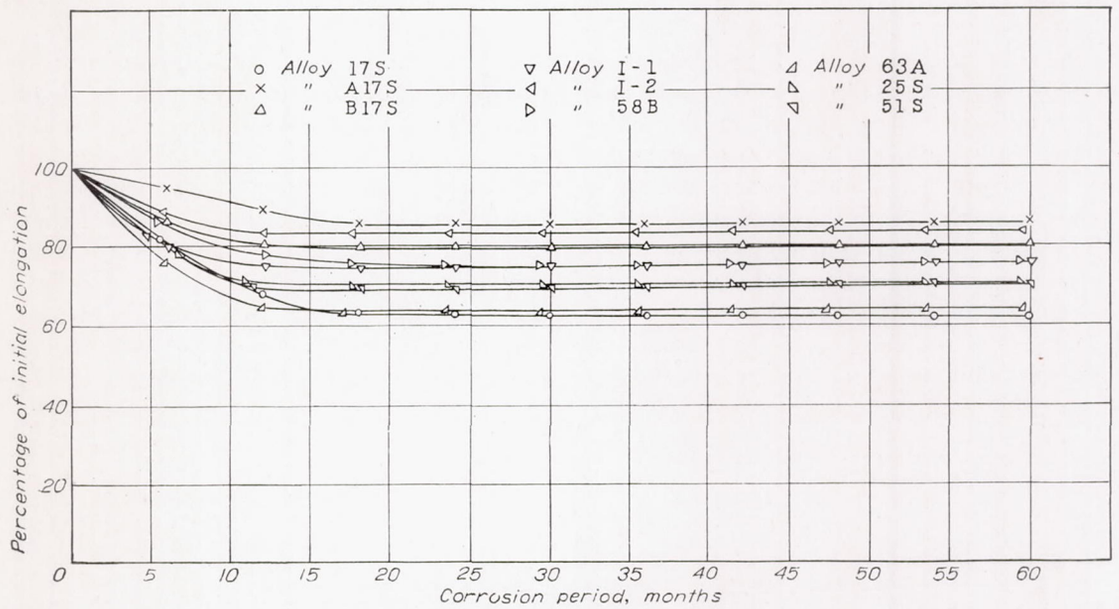



FIGURE 20.—Effect of chemical composition upon the corrosion of aluminum alloys exposed at Hampton Roads. All specimens solution heat-treated, quenched in ice water, and aged 3 months at room temperatures.

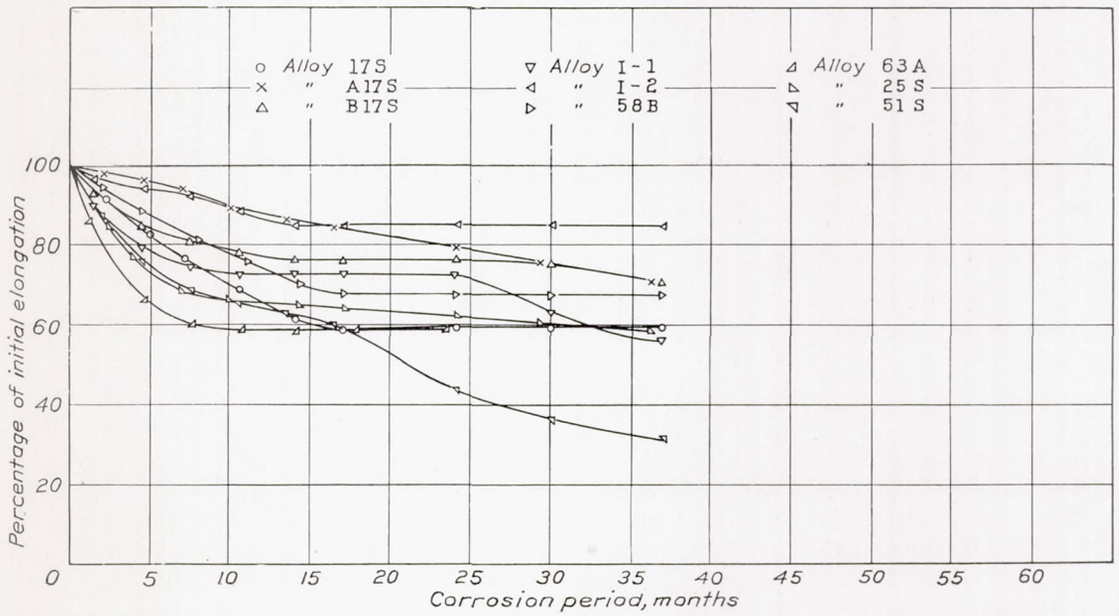



FIGURE 21.—Effect of chemical composition upon the corrosion of aluminum alloys exposed at Coco Solo. All specimens solution heat-treated, quenched in ice water, and aged 3 months at room temperatures.

For alloys varying only slightly from the ordinary duralumin composition it appears certain that the factors of heat treatment, more particularly the method of quenching and subsequent reheating, are of major importance in rendering such material resistant to corrosion. The rôle played by slight variations in chemical composition is, in comparison, a minor one. This is well exemplified in figure 22, which illustrates that duralumin from different manufacturers, when heat-treated in identical manners, were markedly similar in behavior in the weather-exposure tests.

In this connection it is noteworthy that no intercrystalline attack was found on any of the ice-water-quenched specimens of alloys 17S, I–1, I–2, A17S, B17S, 58B, or 63A after exposure. The attack on alloy 51S was predominantly of the pitting type; a

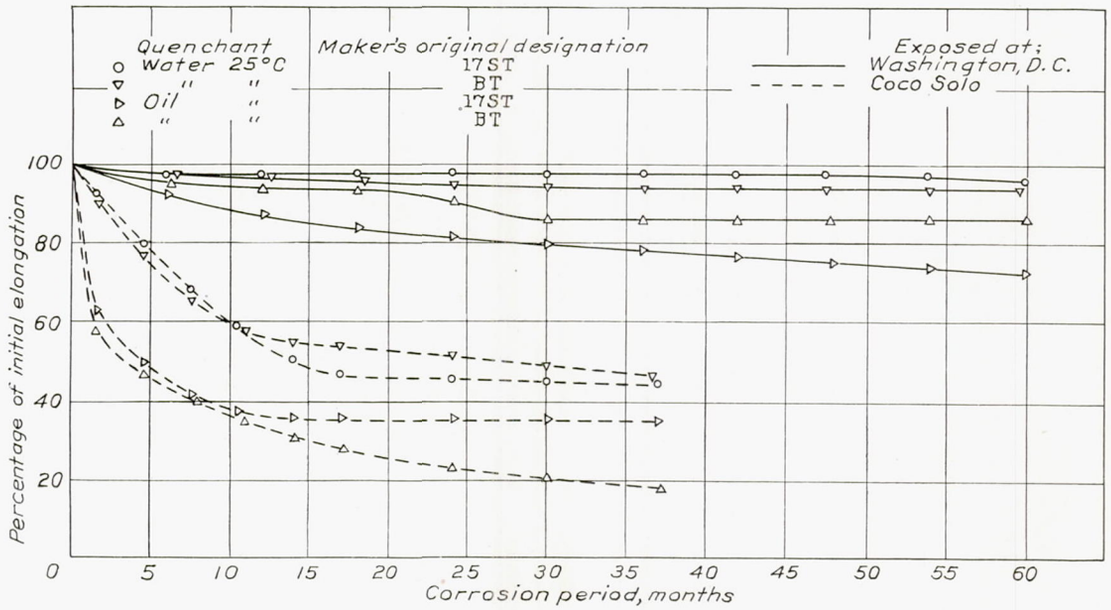



FIGURE 22.—Comparison of corrosion resistances of two duralumins from separate manufacturers. All specimens given a solution heat treatment 15 minutes at 505° C.

few specimens contained areas suggestive of intercrystalline attack, but in no case was it typically developed. The attack on alloy 25S was of a type closely resembling that shown in figure 8d.

### EFFECT OF LOCALITY

Definite information on the effect of the weather at the three localities upon the corrosion of specific aluminum alloys under specific conditions of treatment, has been given for the individual sets in the results presented graphically. Owing to the fact, however, that only a single specimen of each set was removed for test at each interval, the results cannot be regarded as quantitatively accurate. They are better to be regarded as "pilot" tests useful for indicating, within limits of reasonable accuracy, what behavior may be expected at each of the three localities.

In figure 23 are plotted the average elongation and depth of penetration of attack values of at least 40 specimens removed at a given time at each locality, irrespective of their composition, heat treatment, or protective coatings. Thus, with all the other variables taken into consideration, the more general effects of locality of corrosion on the "average" aluminum alloy are emphasized. It is apparent that saline conditions of exposure, as at Hampton Roads or Coco Solo, definitely cause a much more rapid initial rate of loss of ductility.

A comparison of the localities can be made on the basis of an arbitrarily selected value of the percentage of the initial elongation. Let it be assumed that, when the value has fallen below 80, corrosion has resulted in lowering the tensile properties a definite amount (fig. 6). The average value of the utlimate strength for duralumin would then be about 59,000 pounds per square inch, and the elongation approximately 17 percent.

It will be noted (fig. 23) that at Washington the ductility value was still above 80 at the end of 5 years. At Hampton Roads the value, 80, was reached in about 3 months, and was above 50 after 5 years' exposure. At Coco Solo the value, 80, was attained in less than 2 months; at the end of 3½ years it was not below 40. It will be recalled that appreciable losses in tensile strength do not occur in duralumin until this value falls below 40 (fig. 6). The foregoing emphasizes clearly the relative permanence of aluminum alloys in general, the more so since these results were obtained on sheet material only 0.064 inch thick.

However, properly heat-treated aluminum alloy sheet material was found to be much less susceptible to corrosive attack than the data in figure 23 would indicate. In figure 25 are curves plotted on the basis of averages on the five uncoated alloys least susceptible

to corrosive attack. The alloys uniformly represented among the highest values were those designated as I–2, A17S, B17S, 58B, 17S, and, at Washington only, 51S. All specimens were quenched in ice water, after the solution heat treatment, and aged at room temperature.

Exposure to the weather 5 years at Washington resulted in only slight losses in physical properties. At both Hampton Roads and Coco Solo the ductility value was well above 70 after the maximum exposure period. Penetration of corrosive attack, which was invariably of the pitting type, was seldom more than 0.006 inch at the end of 5 years, usually being less than 0.003 inch at Washington. The arrest in corrosive action at the marine localities, following initial attack, is well in evidence from the average of both the elongation and the depth of penetration values.

The relative impermanence of alloys not correctly heat-treated is well exemplified by the curves of figure 26. The curves are based on averages of the five uncoated sets of specimens most susceptible to attack at all three localities. These were all 17S material heated at 505° C. and then treated as follows: (1) Quenched in ice water and aged 3 hours at 150° C.; (2) quenched in boiling water and aged 3 months at room temperature; (3) quenched in boiling water, aged 96 hours at room temperature, and stretched 10 percent of length; (4) quenched in ice water, aged 96 hours at room temperature and reheated 5 hours at 135° C.; (5) quenched in oil at 25° C. and aged 3 months at room temperature.

The exceptionally rapid lowering of the ductility, to values of approximately 20 and below at Hampton Roads and Coco Solo, is especially to be noted. The initial arrest at Washington, however, occurred at a value of about 60. The attack was of the intercrystalline type in all cases. It will be noted in particular that intercrystalline attack may be expected to penetrate entirely 0.064-inch material, exposed under conditions as severe as those prevailing at Coco Solo, in a period of from 3 to 4 years (fig. 24c).

The data in table IV are presented to furnish summarily an approximate idea of the probable behavior of aluminum alloy sheet at the three localities.

#### IMMERSION IN SEA WATER

At Hampton Roads the specimens were placed on the exposure racks on May 5, 1927. Between May 5, 1928, and November 5, 1928, one of the exposure racks accidentally became immersed in the sea water, where it lay until removed early in January 1929. The specimens were therefore continuously immersed for a period of not less than 2 nor more than 8 months. The effects of the immersion are shown in figure 27,

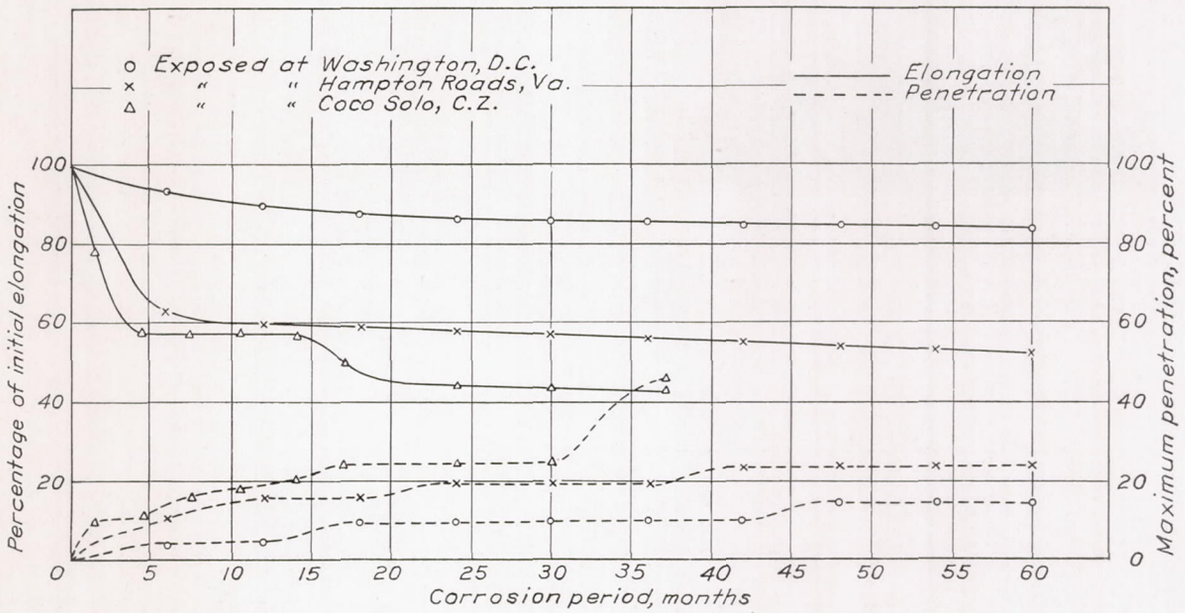



FIGURE 23.—Effect of locality upon the resistance of aluminum alloys to corrosion. Average of 40 materials at each test period.

where the specimens which lay in the sea water were arbitrarily plotted as having been removed after 6 months.

The curves indicate that at the conclusion of the 12-month exposure period the specimens were nearing the end of the initial period of rapid attack. Immersion in the sea water, however, resulted in another period of accelerated attack, during which the tensile properties were lowered to approximately 50,000 pounds per square inch and the elongation to 6.5 percent or lower. It may also be concluded that immersion in sea water should result in a much more rapid initial rate of corrosion than ordinary exposure to saline atmospheres. Some of the immersed specimens were subsequently placed back for weather exposure an additional 3½ years, during which no further marked losses in tensile properties occurred.

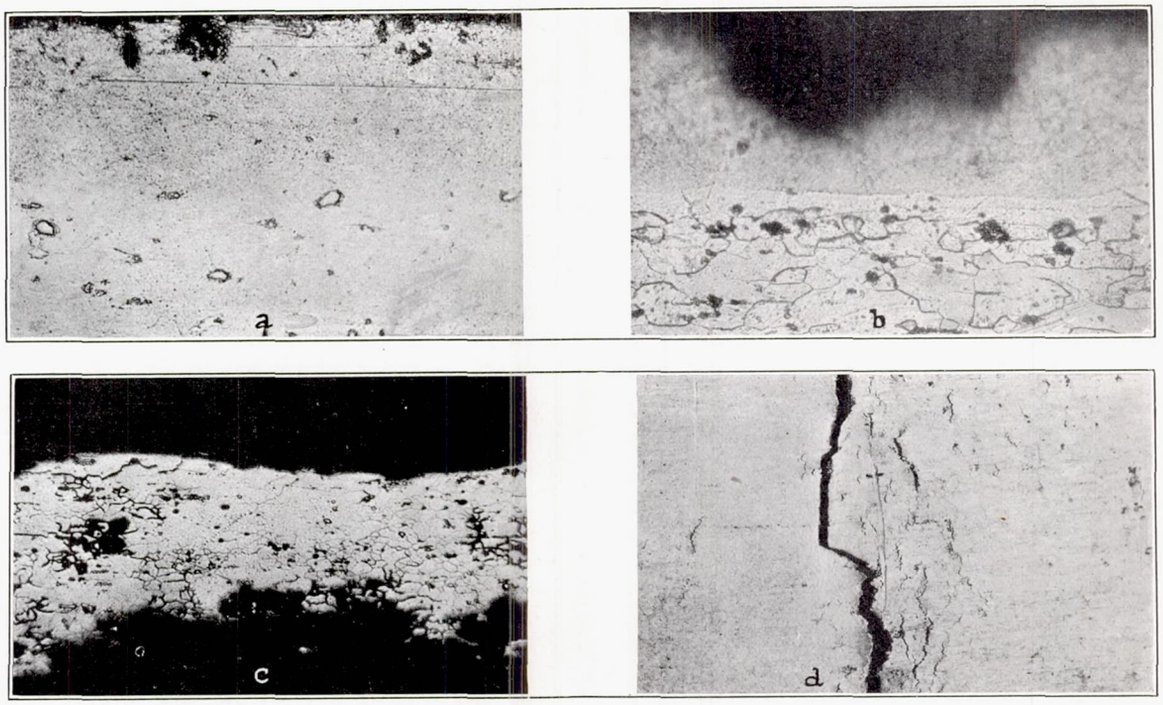



FIGURE 24.—(a) Alclad 17S material (unetched), exposed 5 years at Washington, ×250; (b) Alclad 17S, exposed 5 years at Hampton Roads and etched to show the diffusion zone, ×250; (c) alloy 17S, reheated for 5 hours at 135° C. after solution heat treatment, quenching, and aging 96 hours at room temperatures, ×250; (d) surface cracks ("crazing") developed while breaking an embrittled tensile bar, ×3. Note that corrosion of the Alclad specimens has not penetrated the high purity aluminum coating. Specimen (c) was exposed 3½ years at Coco Solo and most of the original metal has been removed as a result of "pock-form" corrosion. The phenomenon of crazing is frequently encountered in embrittled duralumin.

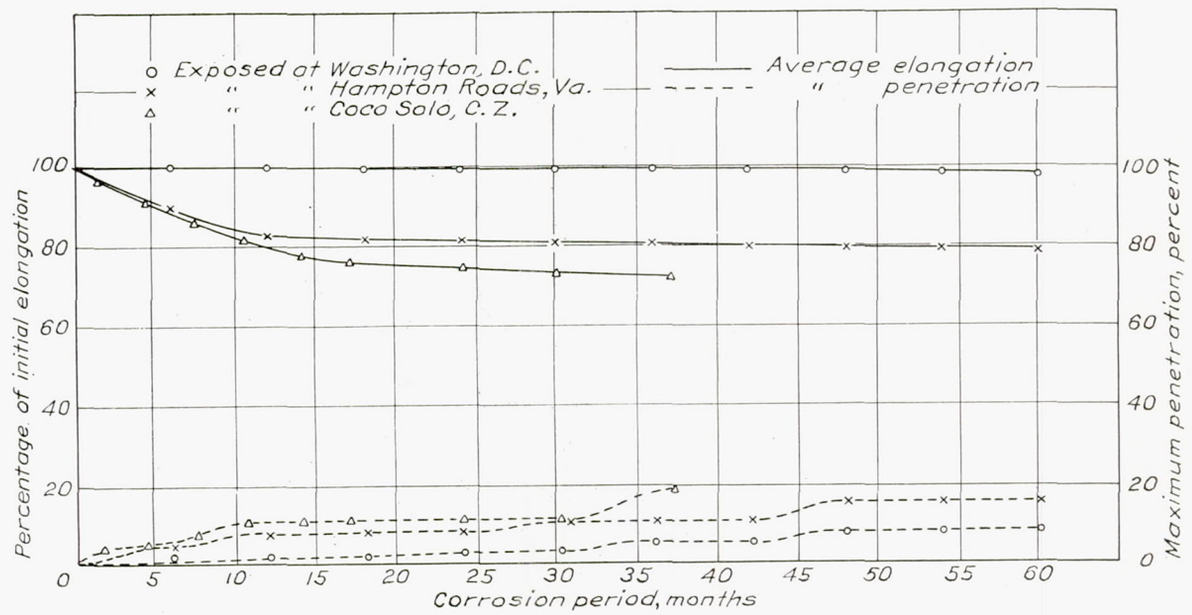



FIGURE 25.—Effect of locality upon the resistance of aluminum alloys to corrosion. Five materials least susceptible to corrosive attack.

### STORAGE IN SEALED CONTAINERS

Specimens stored in the dry atmosphere of the sealed containers for 5 years showed no evidence whatever, on miscroscopic examination, of the presence of corrosive attack. It may, therefore, be concluded that the presence of moisture is an essential factor for corrosion. Neither was there any evidence of losses in tensile properties during the storage period. Both these facts tend to refute a conjecture voiced a number of years ago, as a probable explanation of intercrystalline corrosion phenomena, that alloys of the duralumin type might be subject to spontaneous disintegration.

In general, there was some slight evidence of minor increases in tensile properties, or further age-hardening in the majority of the sets of specimens. The evidence was most pronounced on alloys 25S and 51S, quenched in ice water from 520° C. and aged at room temperatures, and on duralumin which was cold worked by stretching after an aging period at room temperature of only 1 hour. Specimens of alloy 51S and of the stretched duralumin exposed at Washington 5 years actually exhibited properties slightly higher than when originally exposed, as indicated in figures 16 and 19.

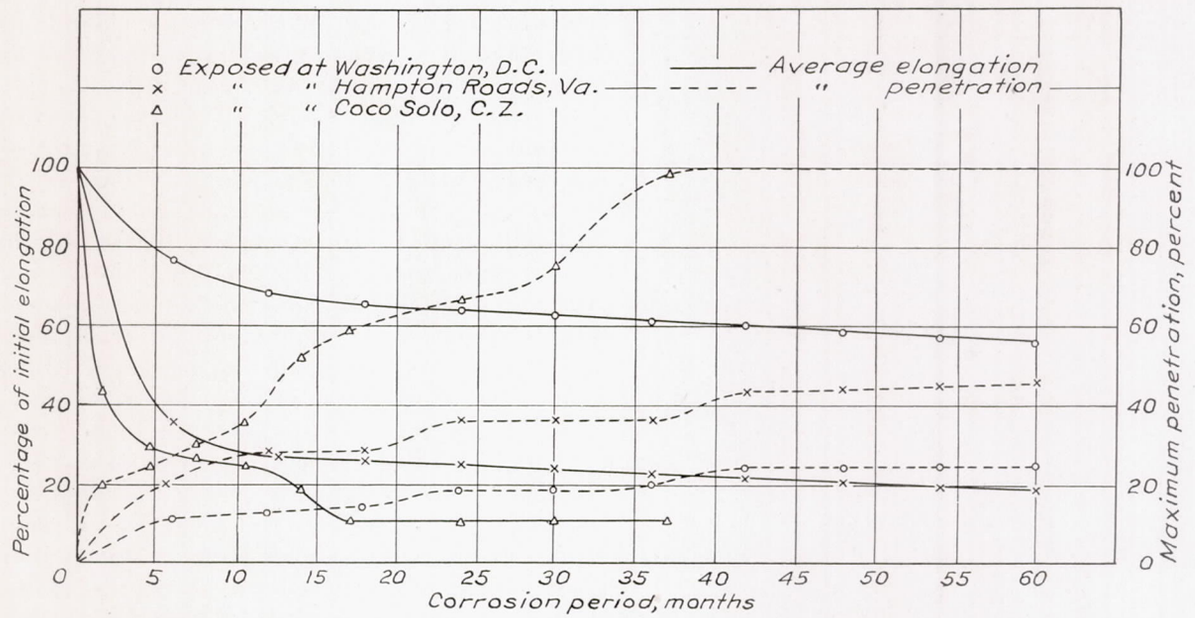



FIGURE 26.—Effect of locality upon the resistance of aluminum alloys to corrosion. Five materials most susceptible to corrosive attack.

### RELATIVE EFFICIENCIES OF PROTECTIVE COATINGS

The advisability of applying protective surface coatings to duralumin to be used under marine conditions has already been indicated. The subject of protective coatings was not investigated systematically in the weather-exposure series, although a number of random coatings were included. There are reviewed here only the results of outstanding importance.

Most of the coatings exposed to the weather were applied to duralumin rendered susceptible to corrosion by quenching in boiling water. Hence, corrosion of the underlying metal with the accompanying loss in tensile properties served as a criterion of the "breakdown" of the coating. A number of the coatings, however, was also applied to duralumin quenched in cold water, to permit more rigid comparison with conditions likely to prevail in actual service.

Surface coatings on aluminum and its alloys may arbitrarily be classified into four principal groups, viz: (1) Metallic coatings; (2) oxide coatings; (3) organic coatings, such as paints, varnishes, lacquers, grease, etc.; and (4) combinations of the oxide and organic coatings. All four classes of coatings were investigated. Only 2 coatings of about 50 tested afforded complete protection to the underlying metal throughout the duration of the exposure tests at all three localities.

The first of these was a sprayed metal coating of pure aluminum prepared in accordance with a suggestion by Dr. H. W. Gillett, contained in a progress report to the sponsors of the project as early as October 1925, which read: "It is thought that a layer of pure aluminum on the surface of duralumin may aid in several ways. It is to be expected that the corrosion of such a layer would be very materially less than that of duralumin. Such a sprayed layer would be light and would afford a very good 'foothold' for any coating applied on top of it."

The coating was applied by metal spraying onto a previously sand-blasted duralumin surface, the specimens being heat-treated after spraying to restore the physical properties which were lowered by the sand-blasting operation. No losses in tensile properties were obtained in laboratory corrosion tests, in the

chloride-peroxide reagent, extending over 2 months. Specimens exposed to the weather under saline conditions for a period of 3 years also exhibited no loss in properties. Loss of the specimens then remaining in the racks made necessary the discontinuance of tests of this set.

The second coating, which gave complete protection over the entire 5 years at Washington and Hampton Roads and the 37-month period at Coco Solo, was of the type marketed commercially under the trade name

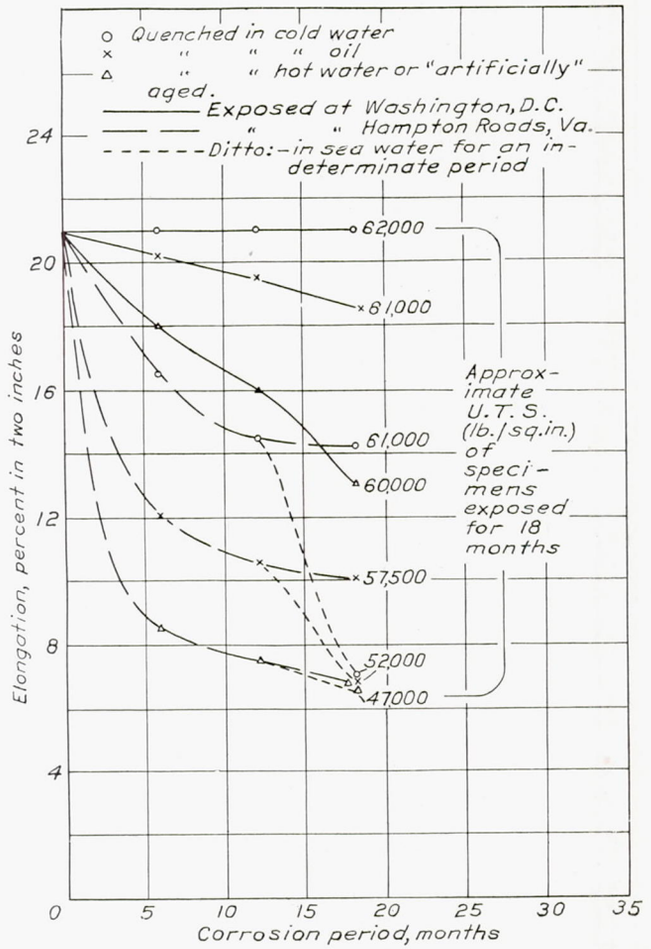



FIGURE 27.—Effect of sea-water immersion on weather-exposure test specimens of 14-gage 17S sheet material. All specimens given a solution heat treatment at 505° C.

"Alclad" (reference 16). The Alclad product tested consisted of a duralumin (17S) base to which a coating of high purity aluminum was integrally bonded through a transition zone of interalloying. The thickness of the coating on each side closely approximated 5 percent of the total thickness of the 0.064-inch sheet.

The Alclad 17S material was exposed to the weather in both the hot- and cold-water-quenched conditions. In neither did the corrosive attack, over the maximum period of exposure, penetrate through the aluminum coating (fig. 24a and b). The ductility values for the material remained consistently above 95. Neither was corrosion observed to any considerable extent on the cut edges of the exposed tensile specimens. Specimens quenched in boiling water and exposed at Washington showed occasional traces of intercrystalline attack on the cut edges after 2 years' exposure, but the tensile properties were not lowered.

The Alclad coating also showed to very marked advantage in the laboratory stress-corrosion tests (reference 6). Its use under conditions of severe static stress or repeated flexural stresses appears especially to be recommended. It was found also to possess certain advantages with respect to the effects of abrasion. A number of Alclad specimens were scratched very severely, with a pair of sharp dividers (fig. 28b). These specimens showed no loss in physical properties after intermittent-immersion tests in the laboratory after 40 days in the chloride-peroxide solution, even when under static stresses of approximately 20,000 pounds per square inch. The presence of relatively light scratches (fig. 28a), however, was found to be very detrimental when flexural stresses of approximately 20,000 pounds per square inch (which are well above the endurance limit) were applied simultaneously with corrosion by the intermittent-immersion method. But no losses in ductility had occurred on any of the scratched specimens after 4½ years' exposure at Washington or Hampton Roads.

The tensile strength of the marketed Alclad 17ST alloy usually averages about 6,000 pounds per square inch lower (based on the total thickness of the sheet) than that of uncoated heat-treated 17S alloy. But when this factor can be neglected, the use of the Alclad sheet under severe corrosive conditions is unquestionably to be recommended in aircraft in preference to duralumin otherwise coated. Coatings of the oxide and organic types applied on Alclad sheet would still further increase its effectiveness.

The following coatings, electrodeposited on duralumin, were included in the weather-exposure test series at Washington: (1) Chromium, 0.00005 inch thick; (2) chromium, 0.0002 inch thick; (3) nickel, 0.0002 inch thick with a chromium finish 0.00005 inch thick. Although initially superficially excellent in appearance, the coatings developed cracks (fig. 28c) and the material showed rapid loss in ductility in less than a year at Washington. These coatings are unquestionably not to be recommended for use in aircraft where resistance to corrosion is an important factor.

In general, oxide-surface coatings alone, or organic-surface coatings alone, gave inadequate protection for long periods under the climatic conditions prevailing at Hampton Roads and Coco Solo. The coating produced by the Bengough anodic process (reference 17) visibly failed at Washington in less than 3 years, and at Hampton Roads and Coco Solo in less than a year. An initial application of grease to the oxide coating

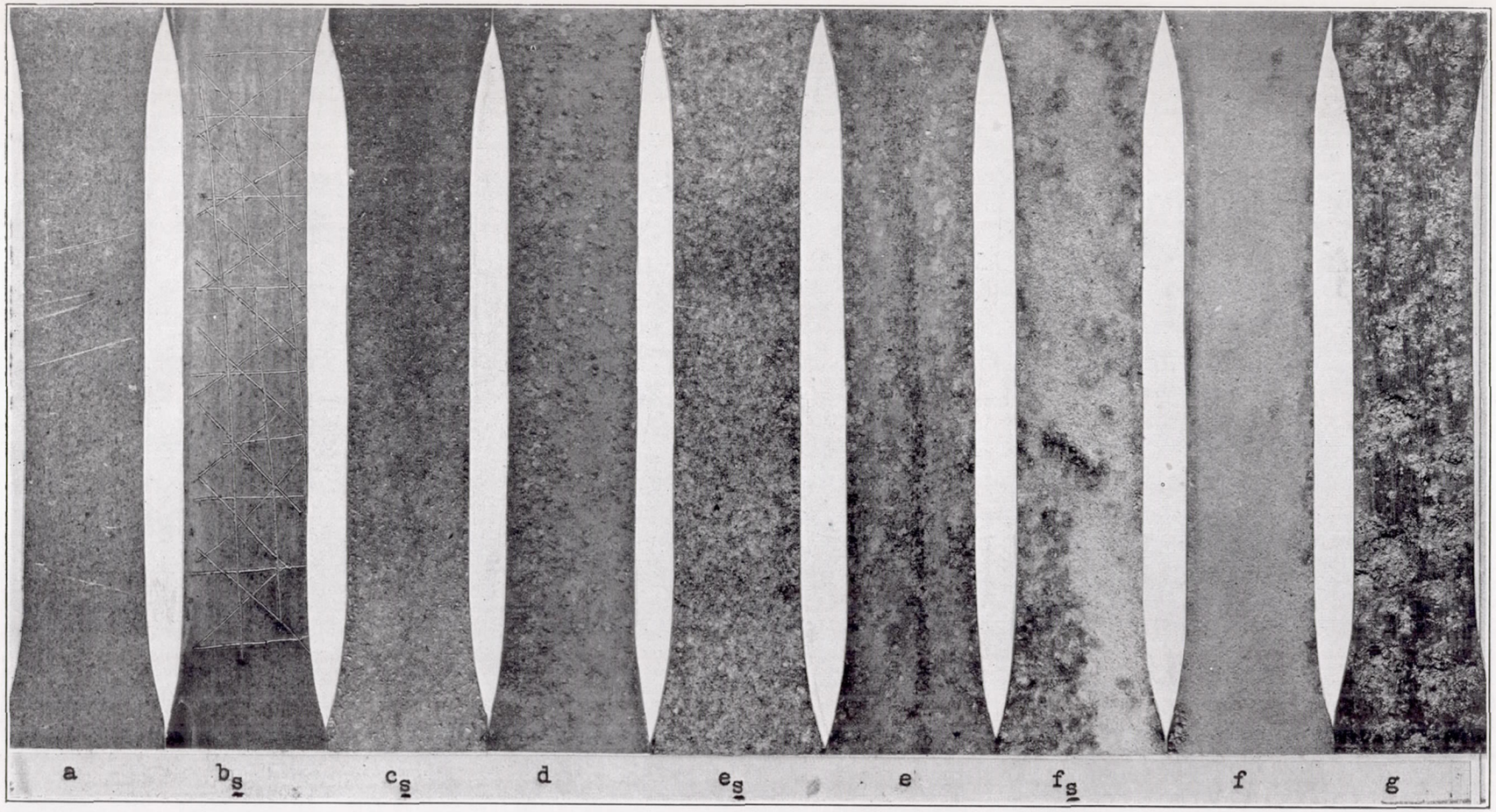



FIGURE 28.—Surface appearance of protective coatings on duralumin after long exposures to the weather. The coatings and exposure conditions: (a) Alclad 17S with 3 light scratches, 4 years at Washington; (b) Alclad 17S with several severe scratches, 3 years at Washington; (c) electroplated coatings of chromium on nickel, 1 year at Washington; (d) Alclad 17S, 5 years at Hampton Roads; (e) Bengough anodic oxide coating, initially greased, 5 years at Hampton Roads; (f) aluminum pigmented spar varnish on Bengough oxide-treated surface, 5 years at Hampton Roads; (g) "chromium varnish" (on alloy 25S), 3½ years at Coco Solo. Note the differences between the skyward and earthward surfaces (cf. figure 9), the former being designated s. The attack in the Alclad specimen, (d), had not penetrated the aluminum coating. The many cracks on (c) attest to the marked inferiority of this coating. Preferential attack on the scratched Alclad specimens, (a) and (b), is not in evidence. ×1.

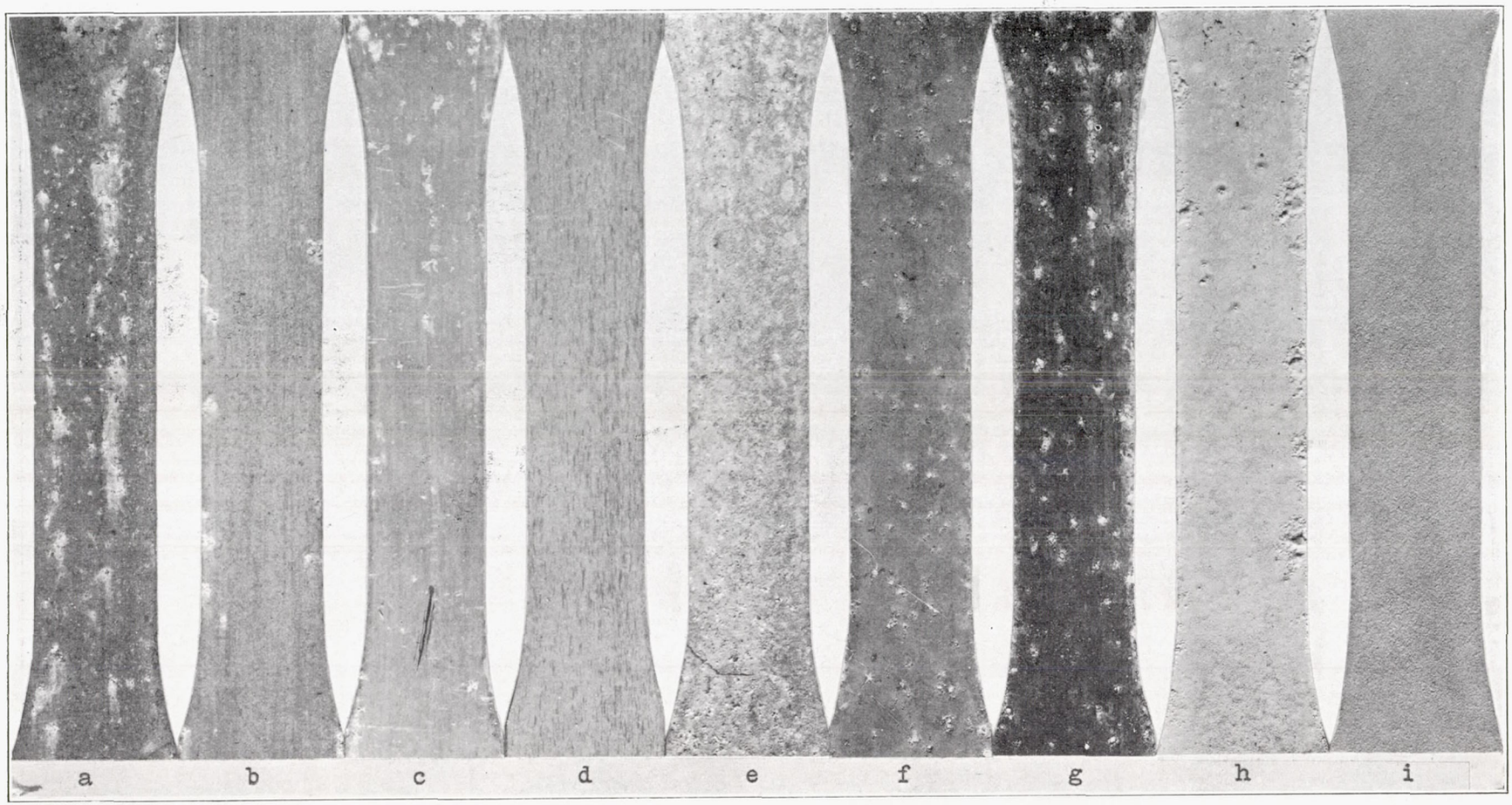



FIGURE 29.—Appearance of protective coatings on duralumin after 4½ months' exposure to the weather at Coco Solo. The skyward surfaces are shown in each instance. (a) Jirotka oxide coating "Ch-h"; (b) Bengough anodically applied oxide coating; (c) Stanley clear lacquer; (d) Stanley clear lacquer on Bengough oxide-treated surface; (e) aluminum pigmented "Rust-Veto" grease; (f) a zinc chromate base paint; (g) carbon black in linseed oil; (h) aluminum pigmented spar varnish; (i) aluminum pigmented spar varnish on Bengough oxide-treated surface. Note especially the superiority of coatings applied to surfaces previously anodically treated. ×1.

gave some additional protection, but was in itself insufficient. The continued application of grease at short intervals would undoubtedly have proved more efficacious but was impracticable in this series of tests. The addition of aluminum powder to greases resulted in markedly increasing their efficiencies as protective agents.

Two organic coatings were outstanding among those applied to duralumin strips whose previous surface treatment consisted simply in being cleaned free from grease. These were: (1) Aluminum "powder" in a vehicle of good grades of long oil varnishes; and (2) a zinc chromate base paint. Neither showed visible evidence of failure after 5 years' exposure at Washington, but did so within 4½ months at Coco Solo (fig. 29).

Better protection was afforded by the same coatings when applied to specimens previously oxidized. The aluminum-pigmented spar varnish coating, when applied to surfaces anodized by the Bengough process, was outstanding among coatings of this type (reference 7). For conditions analogous to those in Washington, combinations of the organic coatings on oxidized surfaces can be relied upon as satisfactory for periods perhaps as long as 2 years. A renewal of the paint coating at that time would appear to be advisable. Although no visible evidence of failure was noticeable, in coatings of this kind there was without doubt some penetration of moisture after 2 years. This was revealed by the loss in ductility of the underlying metal, when it had been intentionally rendered prone to intercrystalline attack. That losses were not detected after 5 years' exposure at Washington, on properly heat-treated metal similarly coated was, of course, to be attributed to the inherent resistance to corrosion of the metal itself.

It has already been pointed out that the position of the specimens in the weather-exposure racks was not changed during the period of their exposure. As a result, the products formed by corrosion usually accumulated in greater amounts, on uncoated specimens, on the surfaces which faced earthward (fig. 9). It may also be seen, by comparing figure 9a, b, and c that the corrosion products accumulated in greater amounts at Coco Solo, being somewhat less at Hampton Roads, and very much less at Washington.

On specimens to which protective organic surface coatings were applied, visible evidences of failure usually occurred first on the skyward surface, presumably owing partly to the action of ultra-violet rays. An example of the relative differences in the appearance of the skyward and earthward surfaces may be seen in figure 28f. Figure 29 reveals the relative efficiencies of certain of the coatings previously discussed, after approximately 4½ months' exposure at Coco Solo. The superiority, in the adherence of varnishes or lacquers which were applied to a surface previously anodically treated, is plainly evident.

## CONCLUSIONS

On the basis of numerous laboratory corrosion tests and weather-exposure tests, conducted over a period of more than 5 years at Washington, D.C., Hampton Roads, Va., and Coco Solo, Canal Zone, the following conclusions appear to be warranted:

1. The type of corrosive attack in duralumin is most frequently one of two distinctive types, viz, pitting or intercrystalline. The method of heat treatment ordinarily plays a much more important rôle than do minor differences in chemical composition in determining which type of attack will develop under corrosive conditions. Moisture is essential to the development of corrosive attack of either type. The type of attack is not materially influenced by variations in the composition of the corroding medium.

2. Aluminum alloy sheet materials of the duralumin type are, when properly heat-treated, to be regarded as thoroughly reliable from the standpoint of relative permanence in service.

3. The method of heat treatment of wrought duralumin is of the utmost importance with respect to its subsequent behavior under conditions conducive to corrosion. Solution heat treatment, quenching, and aging, must each be performed in accordance with the recommendations which follow, if satisfactory corrosion resistance is an objective.

4. Solution heat treatment should be carried out under conditions of accurate control, at temperatures ranging from 500° to 510°C. (930° to 950°F.), for a period sufficient to insure thorough heating. For sheet material approximating thicknesses of 14 gage, a period of from 15 to 30 minutes is satisfactory in a nitrate bath. Prolonged heating at somewhat lower temperatures results in lower tensile properties and relatively inferior corrosion resistance.

5. Quenching should be effected *quickly* into a medium conducive to a rapid rate of cooling. A recommended medium is water at a temperature below 25°C. (77°F.), present in sufficient quantity, with reference to the mass of the metal, to prevent the formation of steam.

6. Age-hardening of duralumin should be permitted to occur at temperatures below 100°C. (212°F.).

7. Quenching in hot water or cold oil, and aging or reheating quenched-and-aged duralumin at temperatures in excess of 100°C. (212°F.) renders duralumin inherently susceptible to the insidious type of attack termed intercrystalline.

8. Intercrystalline attack has been shown, by means of microscopic examinations, to be intimately related to the amount and distribution of the precipitated constituents, particularly $CuAl_2$. The compound $CuAl_2$, however, occurs closely associated with other constituents and may not be the constituent actually attacked during the process of corrosion.

9. Intercrystalline attack tends to increase in depth much more rapidly than that of the pitting type, the former tending to penetrate and the latter to widen. The rate of penetration of both types is a function of the conditions of exposure, being appreciably more rapid, in the initial stages of exposure, in the presence of saline conditions. Chlorides are particularly conducive to rapid rates of corrosive attack in duralumin.

10. An initial period of relatively rapid corrosive attack usually ceases within the first 18 months' exposure, and is followed by one of long duration during which further losses in tensile properties are small.

11. Corrosion in wrought duralumin-type alloys tends to lower the elongation to about 40 percent of its initial value before appreciable losses in tensile strength occur. The latter do not become manifest, in 14-gage sheet duralumin, until corrosive attack has penetrated in excess of a total of 20 percent of the thickness.

12. Cold-working duralumin for slight amounts does not affect its corrosion resistance materially.

13. Alloys prepared from high purity components tend to be more corrosion resistant. High iron contents appear to render aluminum alloys somewhat more susceptible to corrosive attack. Low copper contents tend toward improved corrosion resistance.

14. Protective surface coatings are essential on duralumin if the material is to be used under conditions conducive to rapid corrosion.

15. Electrodeposited coatings of nickel or chromium, or both, are entirely unsuited for use as surface protective coatings in aircraft under corrosive conditions.

16. Surface coatings of the oxide or organic types, when used alone, are inadequate for protection over long periods under severe corrosive conditions.

17. A number of combinations of the oxide and organic type coatings have given adequate protection for satisfactory periods under severe corrosive conditions. Aluminum pigmented spar varnish, applied to a surface anodized by the Bengough process, was found to be particularly efficacious.

18. Protective coatings of aluminum are undoubtedly to be recommended whenever corrosive conditions are severe. Alclad type products were found to be highly resistant to corrosive attack, and exhibited no consistent loss in tensile properties throughout the maximum duration of the weather-exposure tests.

BUREAU OF STANDARDS,
WASHINGTON, D.C., *March 23, 1934.*

**ACKNOWLEDGMENTS**

The author acknowledges his indebtedness to H. S. Rawdon and Dr. H. W. Gillett, under whose immediate supervision much of the work was done and who were jointly responsible for outlining the initial program of tests; to H. N. Solakian, who devoted considerable time to that portion of the investigation involving correlation between the microstructural features associated with the different types of corrosive attack; to R. E. Pollard, who prepared most of the specimens used in the weather-exposure and laboratory corrosion tests; to R. W. Buzzard, who performed the majority of the laboratory stress-corrosion tests and assisted in the microscopic examination of the corroded specimens; and to H. E. Francis, who assisted generally.

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TABLE I

CHEMICAL COMPOSITION OF ALUMINUM ALLOY MATERIALS USED IN THE WEATHER-EXPOSURE TESTS

| Material | Chemical composition (percent) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Al [c] | Cu | Mg | Mn | Fe | Si | Other elements | Elements not detected by tests |
| 17S [a] | 94.39 | 3.9 | 0.65 | 0.54 | 0.28 | 0.24 | ---------- | Cr, Sn, Zn, Ca, Ni. |
| B [a d] | 93.79 | 4.1 | .59 | .60 | .48 | .29 | Cr 0.15 | Sn, Zn, Ca, Ni. |
| I–1 [a] | 94.46 | 4.2 | .47 | .47 | .20 | .20 | ---------- | Sn, Zn, Ni, Pb, Ca. |
| I–1 [b] | 94.44 | 4.14 | .49 | .51 | .22 | .20 | ---------- | Ca. |
| I–2 [a] | 94.63 | 4.2 | .52 | .47 | .08 | .10 | ---------- | Sn, Zn, Ca, Pb, Ni. |
| I–2 [b] | 94.72 | 4.14 | .50 | .51 | .06 | .07 | ---------- | Ca. |
| 58B [a] | 95.01 | 3.1 | .63 | .50 | .55 | .21 | ---------- | Sn, Zn, Ca, Ni. |
| 63A [a] | 93.66 | 3.8 | .63 | .50 | 1.15 | .24 | Ni<.02 | Sn, Zn, Ca. |
| A17S [a] | 96.56 | 2.5 | .40 | .02 | 0.28 | .24 | ---------- | Sn, Zn, Ca, Ni. |
| B17S [a] | 95.25 | 3.7 | .45 | .02 | .36 | .22 | ---------- | Sn, Zn, Ca, Ni. |
| 25S [a] | 93.67 | 4.2 | ----- | .68 | .45 | .9 | ---------- | Sn, Zn, Ca, Ni, Mg. |
| 51S [a] | 97.95 | 0.05 | .61 | .01 | .38 | 1.0 | ---------- | Sn, Zn, Ca, Ni. |

[a] Bureau of Standards analmade by J. A. Scherrer, chemist.
[b] Analysis by manufactureysis r.
[c] By difference.
[d] Duralumin furnished by the Baush Machine Tool Co. The remaining alloys were furnished by the Aluminum Co. of America.

TABLE II

PHYSICAL PROPERTIES AND DEPTH OF PENETRATION OF CORROSIVE ATTACK ON 14-GAGE SHEET ALUMINUM ALLOY MATERIALS AFTER EXPOSURE TO THE WEATHER [a]

| EXPOSURE PERIOD | | TENSILE PROPERTIES | | | | | | | | MAXIMUM DEPTH OF PENETRATION [b] | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Ultimate tensile strength | | | | Elongation in 2 inches | | | | | | |
| Coco Solo only | Other stations | Sealed containers | Washington | Hampton Roads | Coco Solo | Sealed containers | Washington | Hampton Roads | Coco Solo | Washington | Hampton Roads | Coco Solo |
| *Months* | *Months* | *Pounds per square inch* | *Pounds per square inch* | *Pounds per square inch* | *Percent* | *Percent* | *Percent* | *Percent* | *Percent* | *Thousandths of an inch* | *Thousandths of an inch* | *Thousandths of an inch* |
| ALLOY 17S [c]—DURALUMIN OF THE USUAL COMMERCIAL COMPOSITION | | | | | | | | | | | | |
| 0 | 0 | 62,500 | 62,500 | 61,800 | (h) | 19.0 | 20.0 | 21.0 | (h) | 0 | 0 | 0 |
| 1½ | 6 | 61,900 | 61,000 | 57,700 | 60,600 | 20.0 | 21.0 | 15.0 | 20.5 | 1 | 1 | 2 |
| 4½ | 12 | 62,700 | 61,000 | 60,200 | 59,800 | 21.5 | 20.0 | 15.5 | 18.0 | 1 | 5 | 2 |
| 7½ | 18 | 62,100 | 62,500 | [f] 44,800 | 59,000 | 21.5 | 21.0 | [f] 3.5 | 15.5 | 1 | [f] 4 | 3 |
| 10½ | 24 | 62,300 | 61,700 | [f] 45,800 | 60,600 | 21.5 | 21.5 | [f] 4.0 | 14.5 | 3 | [f] 2 | 3 |
| 14 | 30 | 63,200 | 59,200 | [f] 46,000 | 58,750 | 19.5 | 18.0 | [f] 5.0 | 12.0 | 2 | [f] 3 | 4 |
| 17 | 36 | 62,500 | 60,600 | [f] 48,750 | 55,800 | 21.5 | 21.0 | [f] 6.0 | 10.0 | 2 | [f] 5 | 3 |
| 24 | 42 | 62,500 | 60,800 | [f] 50,000 | 58,300 | 21.5 | 21.0 | [f] 6.5 | 12.0 | 2 | [f] 5 | 4 |
| 30 | 48 | 62,900 | 61,000 | [f] 49,000 | 58,500 | 22.0 | 21.0 | [f] 6.0 | 13.5 | 6 | [f] 5 | 6 |
| 37 | 54 | 62,700 | 60,400 | [f] 52,700 | 55,800 | 22.5 | 16.0 | [f] 7.5 | 13.0 | 3 | [f] 6 | 7 |
| -------- | 60 | 63,300 | 59,800 | [f] 55,000 | (g) | 23.5 | 20.5 | [f] 9.0 | (g) | 3 | (h) | (g) |
| ALLOY I–1 [c]—DURALUMIN WITH "CONTROLLED" IRON-SILICON RATIO, APPROXIMATELY 1:1 [e] | | | | | | | | | | | | |
| 0 | 0 | 59,000 | 59,000 | 59,200 | (h) | 20.0 | 20.5 | 20.5 | (h) | 0 | 0 | 0 |
| 1½ | 6 | 58,300 | 54,300 | 53,300 | 55,100 | 20.5 | 20.0 | 17.0 | 18.5 | (h) | 2 | 2 |
| 4½ | 12 | 59,000 | 53,300 | 51,000 | 53,900 | 22.0 | 20.0 | 12.0 | 16.5 | 1 | 2 | 5 |
| 7½ | 18 | 58,500 | 53,900 | 51,000 | 53,500 | 21.5 | 20.0 | 16.0 | 18.0 | [d] 3 | 2 | 5 |
| 10½ | 24 | 55,000 | 55,200 | 52,700 | 54,000 | 20.0 | 20.0 | 15.0 | 14.0 | [d] 2 | [d] 5 | [d] 4 |
| 14 | 30 | 56,250 | 54,400 | 52,500 | 53,750 | 19.5 | 20.5 | 14.5 | 15.0 | 2 | 5 | [d] 7 |
| 17 | 36 | 51,500 | 55,000 | 52,500 | 53,300 | 17.0 | 19.5 | 17.0 | 15.5 | 3 | 4 | [d] 7 |
| 24 | 42 | 58,750 | 53,900 | 52,700 | 53,500 | 21.0 | 19.5 | 15.5 | 15.0 | 3 | 6 | [d] 4 |
| 30 | 48 | 58,750 | 54,400 | 52,700 | 52,000 | 22.0 | 19.5 | 16.0 | 13.0 | 3 | 6 | [d] 7 |
| 37 | 54 | 59,600 | 53,700 | 52,500 | 50,200 | 22.0 | 19.0 | 15.5 | 11.5 | [d] 5 | 7 | 13 |
| -------- | 60 | 59,000 | 53,700 | 52,700 | (g) | 21.0 | 19.5 | 17.5 | (g) | 3 | 6 | (g) |
| ALLOY I–2 [c]—DURALUMIN MADE FROM HIGH PURITY MATERIALS [e] | | | | | | | | | | | | |
| 0 | 0 | 56,900 | 57,900 | 57,300 | (h) | 20.5 | 20.0 | 20.0 | (h) | 0 | 0 | 0 |
| 1½ | 6 | 57,350 | 57,100 | 56,900 | 58,500 | 21.5 | 21.0 | 19.0 | 20.5 | 1 | 2 | 1 |
| 4½ | 12 | 57,500 | 55,900 | 55,200 | 57,900 | 20.0 | 20.0 | 18.5 | 18.0 | 1 | 9 | 2 |
| 7½ | 18 | 58,500 | 57,500 | 54,100 | 58,750 | 23.5 | 21.0 | 17.5 | 21.0 | 2 | 3 | 5 |
| 10½ | 24 | 59,600 | 57,900 | 54,200 | 58,300 | 20.0 | 21.0 | 16.5 | 20.5 | 2 | 9 | 4 |
| 14 | 30 | 56,500 | 58,500 | 55,200 | 56,500 | 20.5 | 22.0 | 17.5 | 18.0 | 1 | 5 | 3 |
| 17 | 36 | 58,750 | 58,750 | 57,300 | 58,300 | 21.5 | 21.5 | 18.0 | 17.5 | 2 | 4 | 4 |
| 24 | 42 | 58,100 | 57,500 | 57,700 | 56,500 | 21.0 | 21.0 | 20.5 | 18.0 | 2 | 6 | 4 |
| 30 | 48 | 59,200 | 57,900 | 55,200 | 56,900 | 21.5 | 21.0 | 18.5 | 18.5 | 2 | 7 | 5 |
| 37 | 54 | 57,100 | 55,800 | 54,200 | 55,400 | 22.5 | 21.0 | 17.0 | 18.0 | 2 | 9 | 6 |
| -------- | 60 | 58,300 | 55,900 | 54,200 | (g) | 22.5 | 21.0 | 16.5 | (g) | 2 | 9 | (g) |
| ALLOY 58B [c]—DURALUMIN-TYPE ALLOY WITH LOW COPPER CONTENT (3.1 PERCENT) [e] | | | | | | | | | | | | |
| 0 | 0 | 51,250 | 52,300 | 51,700 | (h) | 20.0 | 20.0 | 20.5 | (h) | 0 | 0 | 0 |
| 1½ | 6 | 51,900 | 52,300 | 50,800 | 52,500 | 19.0 | 16.5 | 16.5 | 21.0 | 1 | 3 | 1 |
| 4½ | 12 | 52,500 | 51,900 | 51,900 | 51,500 | 21.0 | 20.0 | 17.0 | 17.0 | 2 | 4 | 2 |
| 7½ | 18 | 52,700 | 52,100 | 51,700 | 51,250 | 20.5 | 19.0 | 17.0 | 18.0 | 4 | 3 | 2 |
| 10½ | 24 | 52,700 | 51,600 | 49,800 | 50,800 | 21.0 | 19.0 | 15.5 | 15.0 | [d] 4 | [d] 3 | 2 |
| 14 | 30 | 52,300 | 52,100 | 50,000 | 51,000 | 21.0 | 19.0 | 13.0 | 16.0 | 1 | [d] 4 | 2 |
| 17 | 36 | 51,600 | 51,000 | 51,500 | 51,000 | 21.0 | 19.5 | 17.5 | 14.0 | 2 | 4 | 3 |
| 24 | 42 | 52,500 | 50,800 | 49,200 | 49,800 | 21.5 | 19.0 | 14.0 | 13.5 | 2 | 3 | 4 |
| 30 | 48 | 52,100 | 51,700 | 50,200 | 48,400 | 20.5 | 20.0 | 14.5 | 12.0 | 3 | 5 | 10 |
| 37 | 54 | 53,300 | 50,000 | 50,800 | 50,400 | 20.0 | 14.0 | 17.0 | 15.5 | 4 | 6 | 8 |
| -------- | 60 | 51,800 | 50,800 | 49,600 | (g) | 20.0 | 20.5 | 15.5 | (g) | 2 | 8 | (g) |

See footnotes at end of table

TABLE II—Continued

| EXPOSURE PERIOD | | TENSILE PROPERTIES | | | | | | | | MAXIMUM DEPTH OF PENETRATION | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Ultimate tensile strength | | | | Elongation in 2 inches | | | | | | |
| Coco Solo only | Other stations | Sealed containers | Washington | Hampton Roads | Coco Solo | Sealed containers | Washington | Hampton Roads | Coco Solo | Washington | Hampton Roads | Coco Solo |
| | | ALLOY 63A[c]—DURALUMIN-TYPE ALLOY WITH HIGH IRON CONTENT (1.15 PERCENT)[e] | | | | | | | | | | |
| *Months* | *Months* | *Pounds per square inch* | *Pounds per square inch* | *Pounds per square inch* | *Percent* | *Percent* | *Percent* | *Percent* | *Percent* | *Thousandths of an inch* | *Thousandths of an inch* | *Thousandths of an inch* |
| 0 | 0 | 52,300 | 51,900 | 51,250 | [h] | 20.0 | 19.0 | 19 0 | [h] | 0 | 0 | 0 |
| 1½ | 6 | 50,600 | 51,700 | 48,500 | 51,700 | 19.5 | 16.5 | 10.0 | 15.5 | 1 | 2 | 2 |
| 4½ | 12 | 52,300 | 51,000 | 50,800 | 50,200 | 17.5 | 19.0 | 9.5 | 11.5 | 1 | 2 | 2 |
| 7½ | 18 | 52,300 | 52,300 | 48,000 | 50,400 | 17.5 | 16.5 | 11.0 | 11.0 | 1 | 2 | 2 |
| 10½ | 24 | 51,500 | 52,300 | 48,800 | 50,400 | 14.0 | 15.0 | 11.0 | 10.0 | 4 | 2 | 4 |
| 14 | 30 | 50,600 | 55,400 | 48,500 | 50,400 | 15.5 | 12.5 | 11.5 | 12.0 | 2 | 6 | 3 |
| 17 | 36 | 51,700 | 51,600 | 50,000 | 48,400 | 22.0 | 16.5 | 12.5 | 10.0 | 3 | 5 | 3 |
| 24 | 42 | 52,300 | 51,800 | 51,700 | 49,400 | 18.0 | 15.0 | 13.5 | 11.5 | 2 | 4 | 3 |
| 30 | 48 | 52,300 | 51,600 | 49,800 | [g] | 16.0 | 16.5 | 12.5 | [g] | 2 | 7 | [g] |
| 37 | 54 | 54,000 | 50,000 | 47,500 | [g] | 18.0 | 13.0 | 9.5 | [g] | 4 | 5 | [g] |
| | 60 | 51,700 | 50,800 | 49,600 | [g] | 16.0 | 17.5 | 11.5 | [g] | [h] | 6 | [g] |
| | | ALLOY B17S[c]—"MODIFIED" DURALUMIN-TYPE COMMERCIAL ALLOY WITH LOW COPPER CONTENT (3.7 PERCENT) AND LOW MANGANESE CONTENT (0.02 PERCENT) | | | | | | | | | | |
| 0 | 0 | 50,900 | 51,600 | 52,000 | [h] | 21.5 | 22.5 | 23.5 | [h] | 0 | 0 | 0 |
| 1½ | 6 | 51,800 | 47,700 | 50,450 | 52,300 | 22.5 | 18.0 | 16.5 | 21.5 | 1 | 3 | 8 |
| 4½ | 12 | 52,300 | 50,200 | 50,000 | 49,100 | 23.0 | 19.0 | 18.0 | 18.5 | 1 | 2 | 7 |
| 7½ | 18 | 52,700 | 51,400 | 50,000 | 49,500 | 22.5 | 21.0 | 20.5 | 20.5 | 3 | 5 | 5 |
| 10½ | 24 | 52,700 | 49,300 | 50,200 | 51,800 | 22.5 | 17.0 | 18.5 | 19.0 | 4 | 4 | 5 |
| 14 | 30 | 51,600 | 50,450 | 50,000 | 49,800 | 21.5 | 21.5 | 19.0 | 17.5 | 2 | 4 | 5 |
| 17 | 36 | 51,800 | 50,900 | 50,200 | 49,800 | 22.5 | 21.0 | 18.0 | 17.5 | 3 | 5 | 7 |
| 24 | 42 | 52,300 | 50,200 | 50,450 | 49,500 | 24.0 | 19.0 | 20.0 | 18.0 | 3 | 5 | 10 |
| 30 | 48 | 52,950 | 49,100 | 47,700 | 48,600 | 24.5 | 19.5 | 18.0 | 17.5 | 3 | 5 | [h] |
| 37 | 54 | 52,700 | 49,800 | 50,000 | 46,600 | 24.0 | 17.5 | 18.5 | 16.0 | 3 | 6 | 27 |
| | 60 | 52,300 | 51,500 | 50,000 | [g] | 25.0 | 21.5 | 18.5 | [g] | [h] | 6 | [g] |
| | | ALLOY A17S[c]—"MODIFIED" DURALUMIN-TYPE COMMERCIAL ALLOY WITH LOW COPPER CONTENT (2.5 PERCENT) AND LOW MANGANESE CONTENT (0.02 PERCENT) | | | | | | | | | | |
| 0 | 0 | 36,100 | 37,300 | 37,950 | [h] | 23.5 | 22.5 | 25.0 | [h] | 0 | 0 | 0 |
| 1½ | 6 | 38,400 | 39,100 | 38,400 | 39,500 | 21.0 | 22.5 | 21.0 | 23.5 | [h] | 3 | 5 |
| 4½ | 12 | 37,300 | 38,900 | 38,200 | 38,800 | 21.0 | 19.0 | 20.0 | 21.5 | 3 | 6 | 3 |
| 7½ | 18 | 39,100 | 38,900 | 38,800 | 37,700 | 22.5 | 24.5 | 18.0 | 21.5 | 3 | 6 | 3 |
| 10½ | 24 | 38,600 | 37,950 | 37,300 | 39,500 | 17.5 | 19.0 | 18.0 | 19.0 | 5 | 6 | 5 |
| 14 | 30 | 38,600 | 38,900 | 36,800 | 39,100 | 20.5 | 23.0 | 17.0 | 20.0 | 5 | 6 | 2 |
| 17 | 36 | 36,400 | 38,400 | 36,100 | 37,500 | 20.0 | 22.0 | 16.5 | 18.0 | 3 | 3 | 11 |
| 24 | 42 | 39,300 | 38,400 | 37,000 | 38,600 | 25.5 | 21.0 | 19.5 | 18.0 | 3 | 3 | 10 |
| 30 | 48 | 40,000 | 37,800 | 37,500 | 37,500 | 24.0 | 20.0 | 20.5 | 16.0 | 3 | 9 | 10 |
| 37 | 54 | 38,200 | 38,200 | 37,300 | 36,800 | 19.5 | 22.5 | 19.0 | 16.5 | 3 | 6 | 19 |
| | 60 | 39,800 | 37,300 | 37,500 | [g] | 22.0 | 17.0 | 19.0 | [g] | 3 | 6 | [g] |
| | | ALLOY 25S[d]—DURALUMIN-TYPE COMMERCIAL ALLOY WITH HIGH SILICON CONTENT (0.9 PERCENT) AND NO MAGNESIUM | | | | | | | | | | |
| 0 | 0 | 52,600 | 54,800 | 53,500 | [h] | 20.0 | 21.0 | 21.0 | [h] | 0 | 0 | 0 |
| 1½ | 6 | 55,000 | 55,900 | 52,600 | 56,100 | 20.5 | 21.5 | 16.5 | 21.0 | 1 | 2 | 2 |
| 4½ | 12 | 55,400 | 55,000 | 50,900 | 53,000 | 21.0 | 21.5 | 14.5 | 15.0 | 1 | 4 | 2 |
| 7½ | 18 | 55,400 | 55,400 | 51,700 | 52,400 | 22.0 | 21.5 | 16.0 | 14.5 | 2 | 3 | 4 |
| 10½ | 24 | 56,100 | 54,800 | 52,000 | 51,500 | 22.0 | 21.0 | 15.0 | 14.5 | 4 | 5 | 5 |
| 14 | 30 | 53,900 | 54,350 | 51,700 | 53,700 | 20.0 | 21.0 | 13.0 | 16.0 | 2 | 7 | 4 |
| 17 | 36 | 53,600 | 53,200 | 52,600 | 52,600 | 21.0 | 21.5 | 11.5 | 14.5 | 5 | 4 | 5 |
| 24 | 42 | 55,650 | 54,350 | 52,300 | 50,400 | 22.0 | 20.0 | 17.0 | 12.5 | 3 | 4 | 7 |
| 30 | 48 | 55,900 | 52,300 | 52,000 | 50,200 | 22.0 | 20.0 | 13.5 | 10.5 | 4 | 5 | 4 |
| 37 | 54 | 55,000 | 53,600 | 53,000 | 51,500 | 23.0 | 20.0 | 15.0 | 14.0 | 3 | 5 | 5 |
| | 60 | 55,300 | 52,300 | 50,600 | [g] | 22.5 | 21.5 | 15.5 | [g] | [h] | 6 | [g] |
| | | ALLOY 51S[c]—DURALUMIN-TYPE COMMERCIAL ALLOY WITH LOW COPPER CONTENT (0.05 PERCENT) AND HIGH SILICON CONTENT (1.0 PERCENT) | | | | | | | | | | |
| 0 | 0 | 33,800 | 34,000 | 33,300 | [h] | 26.5 | 30.0 | 26.0 | [h] | 0 | 0 | 0 |
| 1½ | 6 | 35,800 | 35,400 | 34,600 | 35,200 | 26.5 | 28.5 | 19.5 | 27.5 | [h] | 6 | 3 |
| 4½ | 12 | 34,100 | 34,350 | 34,000 | 33,600 | 19.0 | 27.0 | 15.0 | 14.5 | [h] | 8 | 3 |
| 7½ | 18 | 35,650 | 35,600 | 33,500 | 33,900 | 27.5 | 26.0 | 15.0 | 19.0 | 4 | [d] 6 | 9 |
| 10½ | 24 | 36,200 | 35,600 | 33,800 | 34,700 | 27.5 | 27.5 | 19.5 | 18.5 | 3 | [d] 9 | [d] 6 |
| 14 | 30 | 35,200 | 35,650 | 33,800 | 34,350 | 26.0 | 26.5 | 17.5 | 17.0 | 2 | [d] 6 | [d] 5 |
| 17 | 36 | 35,200 | 36,100 | 34,400 | 33,500 | 28.0 | 27.5 | 15.0 | 16.5 | 4 | 9 | 9 |
| 24 | 42 | 36,000 | 36,100 | 34,600 | 31,100 | 29.0 | 26.5 | 18.0 | 11.0 | [d] 4 | 9 | 7 |
| 30 | 48 | 36,700 | 36,700 | 34,100 | 30,400 | 28.0 | 26.5 | 20.0 | 9.0 | 6 | 8 | 8 |
| 37 | 54 | 35,900 | 35,900 | 34,100 | 29,100 | 29.0 | 26.5 | 19.5 | 8.5 | [d] 5 | [d] 7 | 18 |
| | 60 | 36,700 | 36,100 | 33,900 | [g] | 29.0 | 27.5 | 18.0 | [g] | [h] | 11 | [g] |

[a] All alloys, except 25S and 51S, were given a solution heat treatment at 505° C. for 15 minutes in a fused nitrate bath, quenched in ice water, and aged 3 months at room temperature, prior to exposure to the weather or otherwise testing. The treatments applied to alloys 25S and 51S1 differed only in that the solution heat treatment-temperature was 520° C.

[b] Measured from the earthward surface of the specimens. The maximum depth of penetration from the skyward surface was usually less than that recorded.

[c] Corrosive attack was confined to the pitting type on each specimen (fig. 8c), except where otherwise indicated.

[d] Corrosive attack closely resembled the intermediate type (fig. 8d).

[e] Alloy prepared specifically for use in the present investigation.

[f] Lay in sea water for an inderterminate period, less than 8 months, but more than 2 months.

[g] Specimen lost.

[h] No test or measurement made.

## TABLE III

TENSILE PROPERTIES OF DURALUMIN (17S) SPECIMENS IN THEIR INITIAL (UNCORRODED) CONDITIONS AFTER BEING GIVEN THE TREATMENTS INDICATED AND AGED AT ROOM TEMPERATURES FOR AN ADDITIONAL 3 MONTHS

| Solution heat treatment | | Quenchant water temperature | Period aged at room temperature | Cold-working | Tensile properties | |
|---|---|---|---|---|---|---|
| Temperature | Time | | | | Ultimate tensile strength | Elongation in 2 inches |
| ° C. | | ° C. | | | *Lb./in.²* | *Percent* |
| 505 | 15 minutes | 2 | 3 months [a] | None | 62,500 | 19.0 |
| 505 | do | 2 | do | do | 62,500 | 20.0 |
| 505 | do | 2 | do | do | 61,900 | 21.0 |
| 505 | 15 minutes | 2 | 1 hour | Stretched 10 percent. | 58,400 | 11.5 |
| 505 | do | 2 | do | do | 56,300 | 11.0 |
| 505 | do | 2 | do | do | 59,600 | 10.5 |
| 505 | 15 minutes | 2 | 96 hours | Stretched 10 percent. | 67,300 | 9.0 |
| 505 | do | 2 | do | do | 67,950 | 13.0 |
| 505 | do | 2 | do | do | 66,800 | 13.0 |
| 505 | 15 minutes | 100 | 96 hours | Stretched 10 percent. | 66,600 | 11.0 |
| 505 | do | 100 | do | do | 68,400 | 11.0 |
| 505 | do | 100 | do | do | 66,300 | 9.5 |
| 505 | 15 minutes | 2 | 3 weeks | Cold-rolled 10 percent. | 69,300 | 11.0 |
| 505 | do | 2 | do | do | 70,900 | 11.5 |
| 505 | do | 2 | do | do | 71,000 | 11.0 |
| 425 | 15 minutes | 25 | 3 months [a] | None | 45,500 | 19.0 |
| 425 | do | 25 | do | do | 44,900 | 21.5 |
| 425 | do | 25 | do | do | 45,500 | 19.0 |
| 425 | 1 hour | 25 | 3 months [a] | None | 48,900 | 20.0 |
| 425 | do | 25 | do | do | 48,100 | 18.5 |
| 425 | do | 25 | do | do | 48,300 | 18.5 |
| 425 | 5 hours | 25 | 3 months [a] | None | 46,500 | 21.0 |
| 425 | do | 25 | do | do | 47,100 | 19.5 |
| 425 | do | 25 | do | do | 46,600 | 18.5 |

[a] No additional aging period.

## TABLE IV

THE APPROXIMATE LENGTH OF TIME, IN MONTHS, REQUIRED FOR THE ELONGATION VALUES OF ALUMINUM ALLOYS TO FALL BELOW THE DESIGNATED AMOUNTS, AS DETERMINED IN THE WEATHER-EXPOSURE TESTS

| Percentage of initial elongation | Months required at locality to fall below elongation value | | | | | |
|---|---|---|---|---|---|---|
| | Alloys resistant to corrosive attack | | | Alloys susceptible to intercrystalline attack | | |
| | Washington, D.C. | Hampton Roads, Va. | Coco Solo, Canal Zone | Washington, D.C. | Hampton Roads, Va. | Coco Solo, Canal Zone |
| 80 | ([a]) | 24 | 18 | 6 | 1 | ½ |
| 60 | ([a]) | ([b]) | ([b]) | 48 | 3 | 1 |
| 40 | ([a]) | ([b]) | ([b]) | ([c]) | 5 | 2 |

[a] Value did not fall below 90 during the entire exposure period.
[b] Value did not fall below 70 during the entire exposure period.
[c] Value did not fall below 50 during the entire exposure period.

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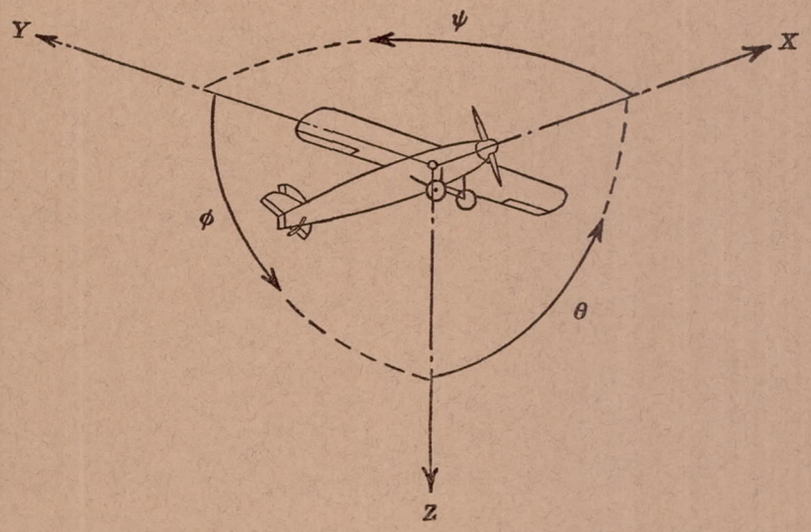


Positive directions of axes and angles (forces and moments) are shown by arrows

| Axis | | Force (parallel to axis) symbol | Moment about axis | | | Angle | | Velocities | |
|---|---|---|---|---|---|---|---|---|---|
| Designation | Symbol | | Designation | Symbol | Positive direction | Designation | Symbol | Linear (component along axis) | Angular |
| Longitudinal | $X$ | $X$ | Rolling | $L$ | $Y \longrightarrow Z$ | Roll | $\phi$ | $u$ | $p$ |
| Lateral | $Y$ | $Y$ | Pitching | $M$ | $Z \longrightarrow X$ | Pitch | $\theta$ | $v$ | $q$ |
| Normal | $Z$ | $Z$ | Yawing | $N$ | $X \longrightarrow Y$ | Yaw | $\psi$ | $w$ | $r$ |

Absolute coefficients of moment

$C_l = \frac{L}{qbS}$ (rolling) $\quad C_m = \frac{M}{qcS}$ (pitching) $\quad C_n = \frac{N}{qbS}$ (yawing)

Angle of set of control surface (relative to neutral position), $\delta$. (Indicate surface by proper subscript.)

## 4. PROPELLER SYMBOLS

$D$, Diameter

$p$, Geometric pitch

$p/D$, Pitch ratio

$V'$, Inflow velocity

$V_s$, Slipstream velocity

$T$, Thrust, absolute coefficient $C_T = \frac{T}{\rho n^2 D^4}$

$Q$, Torque, absolute coefficient $C_Q = \frac{Q}{\rho n^2 D^5}$

$P$, Power, absolute coefficient $C_P = \frac{P}{\rho n^3 D^5}$

$C_s$, Speed-power coefficient $= \sqrt[5]{\frac{\rho V^5}{P n^2}}$

$\eta$, Efficiency

$n$, Revolutions per second, r.p.s.

$\Phi$, Effective helix angle $= \tan^{-1}\left(\frac{V}{2\pi r n}\right)$

## 5. NUMERICAL RELATIONS

1 hp. = 76.04 kg-m/s = 550 ft-lb./sec.

1 metric horsepower = 1.0132 hp.

1 m.p.h. = 0.4470 m.p.s.

1 m.p.s. = 2.2369 m.p.h

1 lb. = 0.4536 kg.

1 kg = 2.2046 lb.

1 mi. = 1,609.35 m = 5,280 ft.

1 m = 3.2808 ft.

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